

**Effect of Climate Change Exposure on Firm Financial Outcomes:
Global Evidence from the Role of TCFD**

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ABSTRACT

Using a global dataset of 6,229 firms from 48 countries (2002–2021), this study examines how CCE affects financial outcomes, particularly in high-carbon-emission firms, and explores the moderating role of TCFD participation. The results show that CCE increases a firm's default risk and reduces value, with greater vulnerability in carbon-intensive industries. Moreover, TCFD participation mitigates these adverse effects of climate change exposure on financial outcomes. These findings suggest that engaging with the TCFD framework effectively addresses climate-related challenges, reduces default risk, and increases firm value, underscoring the strategic value of transparent climate risk disclosure in strengthening financial resilience. The study employs PSM to address potential endogeneity issues, confirming the primary results robustly. Additionally, companies implementing the TCFD framework more effectively mitigate the adverse effects of CCE on financial outcomes, which is pronounced for firms in civil law countries than in common law countries. This study extends the literature by integrating stakeholder theory, the resource-based view, and signaling theory to comprehensively understand how climate risk and mitigation strategies shape financial outcomes. The findings offer critical insights into climate risk management and sustainable corporate strategy, highlighting the importance of TCFD participation and legal systems in moderating the adverse effects of environmental change threats.

Keywords: Firm-level climate change exposure, Firm's default risk, Firm value, the Task Force on Climate-related Financial Disclosures (TCFD).

ABBREVIATIONS

| | |
|-------|---|
| CCE | Firm-level climate change exposure |
| CDP | The Climate Disclosure Project |
| CRI | Global Climate Risk Index |
| DTD | Distance to default |
| OPE | Firm-level climate change exposure for opportunity |
| PD-1m | Probability of default within one month |
| PD-1Y | Probability of default within 1 year |
| PD-2Y | Probability of default within 2 year |
| PD-3m | Probability of default within three months |
| PD-6m | Probability of default within six months |
| PHE | Firm-level climate change exposure for physical |
| RGE | Firm-level climate change exposure for regulatory |
| TCFD | The Task Force on Climate-Related Financial Disclosures |

1. Introduction

Climate change has emerged as a critical challenge for firms, posing both physical and transition risks that significantly affect financial performance and stability (Agoraki et al., 2023; Battiston et al., 2021; Ferdous et al., 2024; Hong et al., 2019; Matsumura et al., 2014, 2024; Reboredo & Ugolini, 2022). These risks include extreme weather events, regulatory pressures, and shifting market dynamics, which collectively undermine firm value and elevate financial risk (Naseer et al., 2024; Sun et al., 2024). For example, in 2020, climate-related disasters resulted in economic damages exceeding \$95 billion in the U.S. (NOAA, 2020), highlighting the urgency of addressing climate risk at the firm level. While prior studies have explored the financial implications of climate risks, significant gaps remain in understanding how structured climate disclosures, such as those aligned with the Task Force on Climate-related Financial Disclosures (TCFD), can mitigate these adverse effects.

Existing research demonstrates that firm-level climate risks can increase firm risk and decrease firm value by reducing profitability, increasing financial uncertainty, and intensifying reputational challenges (Hong et al., 2019; Li et al., 2024; Matsumura et al., 2014; Reboredo & Ugolini, 2022; Vestrelli et al., 2024). However, most studies do not account for the heterogeneity of firms' carbon emissions, leaving unresolved questions about how these risks disproportionately affect high-carbon-emission firms. Additionally, prior studies provide limited evidence on the moderating effects of structured climate disclosure frameworks, such as TCFD, in mitigating climate-related financial risks (Atif & Ali, 2021; Ding et al., 2023; Vestrelli et al., 2024). Addressing these gaps is critical for advancing stakeholder theory (Freeman, 2010), which emphasizes the importance of engaging stakeholders through transparency and accountability, as well as signaling theory (Spence, 1974), which suggests that robust climate-related disclosures signal firms' commitment to managing risks and opportunities effectively.

The growing demand for standardized climate-related information has driven firms to adopt structured disclosure practices. In 2015, the Financial Stability Board initiated the TCFD to enhance the consistency and utility of climate risk and opportunity reporting. By 2017, the TCFD had released a set of recommendations structured with four

fundamental pillars: governance, strategy, risk management, and metrics and targets (TCFD, 2017). These guidelines align with frameworks such as the Carbon Disclosure Project (CDP) and the Global Reporting Initiative (GRI), which are designed to support organizations in disclosing climate-related information relevant to their financial performance (Ngo et al., 2023; TCFD, 2017).

The role of TCFD participation in mitigating the financial impacts of climate risks is supported by three key arguments. First, enhanced climate-related disclosures foster stronger relationships with stakeholders, including investors, customers, and regulators, by signaling transparency and accountability (Dhaliwal et al., 2011; Vilanova et al., 2009). Second, TCFD-aligned disclosures encourage firms to strengthen internal control mechanisms, ensuring compliance with regulations and alignment with stakeholders' interests (Cheng et al., 2014). Third, prior studies highlight that firms with strong environmental performance emphasize their successes through disclosures, while poor performers over-disclose to counteract their weak carbon profiles (Aerts et al., 2008; Ding et al., 2023; Li et al., 2018). Thus, TCFD participation aligns firms with global best practices, enhancing credibility and reducing perceived risks among stakeholders.

Unlike prior research focusing on broad environmental, social, and governance (ESG) disclosures (Cheng et al., 2014; Dhaliwal et al., 2011), this study narrows its scope to climate-specific risks and the role of standardized reporting frameworks. Specifically, it addresses critical research questions: 1) How do firm-level climate change exposure (CCE) impact firm risk and value, particularly for high-carbon-emission firms? 2) To what extent does TCFD participation reduce the financial impacts of CCE? 3) How robust are these findings to endogeneity concerns, such as self-selection into TCFD participation? 4) How do legal frameworks (common law vs. civil law) impact the relationship between CCE and financial outcomes?

Using a global dataset spanning 48 countries from 2002 to 2021, this study integrates firm-level climate risk exposure, industry-level carbon emissions, and TCFD participation into a unified analytical framework. The empirical analysis utilizes panel data linear regression and propensity score matching (PSM) methods to address potential biases and ensure robust findings. This study finds that CCE increases firm default risk

and decreases firm value, particularly among firms operating in high-emission sectors such as industrial, materials, energy, and utilities. These findings emphasize the financial vulnerability of carbon-intensive industries to climate-related shocks. In addition, participation in the TCFD framework attenuates the positive relationship between firm-level climate risk and firm risk, demonstrating the strategic value of climate-related disclosures. This finding emphasizes the role of TCFD as a mitigating mechanism and represents a novel contribution to the literature. In addition, the findings reveal that the effects of CCE on the financial outcomes of firms operating in civil law countries are more pronounced than in common law, with a significant decrease in firm value and an increase in default risk. This divergence suggests that firms in civil law countries with more prescriptive regulatory environments are more likely to benefit from adopting TCFD disclosures to manage climate-related financial risks effectively. However, the benefits of TCFD participation appear to be less pronounced in common law countries, where market-driven mechanisms and less stringent regulations may limit the effectiveness of such disclosures.

This research advances the growing body of literature on climate change risk and corporate strategy by exploring the impact of TCFD-aligned disclosures on the nexus between firm-level risk of climate change exposure and financial outcomes. The findings have practical implications for corporate strategists and decision-makers balancing financial performance with sustainability goals. As investors increasingly prioritize climate accountability, firms adopting effective climate risk management practices are better positioned to enhance firm value, reduce risks, and ensure long-term resilience. By integrating climate risk into business strategy, this study underscores the importance of fostering financial stability and sustainable growth in an era of heightened environmental challenges. For practitioners, the study underscores that proactive climate disclosure is not just a matter of compliance but a strategic tool for building resilience in the face of climate change. By adhering to TCFD guidelines, firms can improve transparency and manage climate-related risks more effectively, contributing to long-term sustainability.

The theoretical framework of this study draws on stakeholder theory, which underscores the importance of addressing stakeholder interests in mitigating firm risks

and enhancing value (Freeman, 2010). By aligning with TCFD recommendations, firms signal their commitment to addressing climate risks and building stronger relationships with investors, customers, and regulators. This study aligns with legitimacy theory, emphasizing that effective climate risk management enhances organizational resilience, maintains legitimacy, addresses stakeholder concerns, and enhances competitive advantage. Furthermore, this study strengthens the signaling theory (Spence, 1974), by showing that TCFD participation acts as a signal of proactive climate risk management, helping firms mitigate the adverse effects of climate risks on their financial performance.

2. Theoretical foundations and hypothesis development

2.1 Theoretical background

2.1.1 Legitimacy theory

Legitimacy theory emphasizes the significance of companies prioritizing the well-being of the broader society instead of just their shareholders' interests (Neu et al., 1998; Pellegrino & Lodhia, 2012). To maintain legitimacy, firms must adapt to evolving societal expectations (Deegan, 2014; Donaldson & Preston, 1995; Huang & Kung, 2010). A key strategy for influencing public perception and preserving legitimacy is disclosing social and environmental information (Brown & Deegan, 1998; Clarkson et al., 2008; De Villiers & van Staden, 2006; Huang & Kung, 2010; Neu et al., 1998). Businesses align their behaviors and messaging with societal values to foster trust and recognition (Islam et al., 2021; Li et al., 2018; Woodward et al., 2001). Empirical studies support the legitimacy theory. For instance, Deegan et al. (2000) discover that Australian corporations increase social disclosures following significant accidents, especially in the affected industries. Likewise, Luo (2019) and Luo and Tang (2021) document a negative relationship between carbon emission intensity and voluntary carbon disclosure, reinforcing the theory's premise that corporations manage public perception through selective reporting. They imply that companies with low ESG performance may reveal more environmental data to conceal their situation and create a positive public image (Cho et al., 2006; Lee & Raschke, 2023; Luo, 2019; Patten, 2002).

Regarding climate change risk management, firms across diverse sectors confront regulatory risks—including the emergence of new regulations and the imposition of

stricter standards (Suchman, 1995). Thus, firms strive to uphold a positive reputation, gain societal acceptance, and adopt strategies to maintain and develop sustainability. The firms' efforts involve detailing specific risks their companies face, their understanding of these risks, their strategies for adaptation and mitigation, and their goals for reducing greenhouse gas emissions. This study draws on legitimacy theory to hypothesize how a firm's environmental risk disclosure influences the association between CCE and financial performance. Additionally, this research considers firm-specific characteristics to address potential omitted variables and account for firm differences.

2.1.2 Stakeholder theory

According to stakeholder theory, managers aim to fulfill stakeholders' expectations as they control essential resources (Deegan, 2002; Donaldson & Preston, 1995; Freeman, 2010). This theory elucidates how managers make decisions regarding environmental disclosures, as discussed by Islam and Roberts (1992), Hughes et al. (2001), and Waheed et al. (2024). Revealing CSR data decreases information asymmetry, aligns stakeholder concerns, boosts reputation, decreases capital expenses, and draws in investors (Deegan, 2002; Freeman, 2010; Mahajan et al., 2023). Therefore, environmental disclosure plays a role in managing relationships with stakeholders and preserving reputation, which aligns with the connection between environmental performance and disclosure. Previous research indicates that stakeholders in corporations are placing more importance on not just making a profit but also on creating positive social and environmental effects (Dyck et al., 2019; Fafaliou et al., 2022; Hartzmark & Sussman, 2019)

It is understood that stakeholders may punish companies for environmental shortcomings, which can escalate potential risks. Investors, suppliers, and consumers pressure companies to disclose and decrease greenhouse gas emissions, impacting climate risk management. Hence, companies that neglect these requirements risk harming their image and forfeiting stakeholder backing. This theory links with the TCFD framework since the TCFD mandates that enterprises evaluate physical risks and transition risks, providing a consistent process for disclosing climate-related risks. This reporting promotes transparency by allowing stakeholders to assess companies' vulnerability,

ability to recover, and preparedness in handling climate-related risks. According to these findings, this research supports the stakeholder value perspective by indicating that TCFD assists companies in lessening risks related to events, lawsuits, the environment, society, governance, and finance. TCFD helps to decrease information imbalances and expenses related to adverse selection, enhancing investor confidence and backing companies' plans. Hence, the connection of climate risk management with financial performance and growth opportunities is essential for TCFD.

2.2 Literature review

Academics have been attempting to address a key question: Can companies improve their financial performance by enhancing their environmental, social, and governance practices? Evidence strongly links improved ESG performance to better financial outcomes. Meta-analyses by Gillan et al. (2021) and Friede et al. (2015) document a predominantly positive correlation between ESG and financial performance. Additionally, prior studies document that ESG scores significantly reduce companies' cost of equity (El Ghouli et al., 2011), lower the cost of debt (Chen & Pham, 2023), and enhance corporate intellectual capital (Pham et al., 2024). Albuquerque et al. (2019) also employ instrumental variable estimation to show a causal connection between ESG and lower systematic risk and higher valuations, consistent with Krueger (2015). These studies suggest that firms with ethical practices are more highly valued and experience lower risk.

The climate change exposure literature identifies three primary dimensions of risk. First, physical risk arises from a company's vulnerability to carbon dioxide emissions and environmental changes, such as rising sea levels. This type of risk is closely associated with significant financial losses for large corporations due to asset damage and disruptions to operations (Chava, 2014; Hong et al., 2019). Second, transition risk pertains to the challenges and innovations required during a firm's shift towards environmentally sustainable practices. This risk encompasses adopting new technologies and processes to align with a low-carbon economy (Bolton & Kacperczyk, 2021; Johnstone et al., 2020). Lastly, regulatory risk emerges from changes in legislation and policies designed to reduce the environmental impact of corporate activities. Compliance

with these regulations often necessitates financial and operational adjustments (Sautner et al., 2023b).

Extensive research underscores the critical impact of climate change risk—both internal and external sources—on a firm’s ability to attract financing (Huang et al., 2018; Kling et al., 2021; Li et al., 2024; Matsumura et al., 2014; Naseer et al., 2024; Secinaro et al., 2020). Additionally, climate risk exposure significantly influences various financial aspects, such as firm valuation, stock returns, cash holdings, and corporate governance (Bolton & Kacperczyk, 2021; Chava, 2014; Hong et al., 2019; Javadi et al., 2023; Matsumura et al., 2014). Among these factors, regulatory risk is increasingly the foremost environmental challenge confronting firms today, with profound implications for financial performance (Cumming et al., 2024; Stroebel & Wurgler, 2021). La Porta et al. (1998) and Horváthová (2010) assert that superior environmental performance is more likely to yield positive financial outcomes in common-law countries, such as Canada and the United States, rather than civil-law nations in continental Europe. Similarly, firms operating under limited regulatory oversight, with smaller workforces and standardized products, are less inclined to realize financial benefits from enhanced environmental performance (Ambec & Lanoie, 2008). Empirical evidence indicates that inadequate environmental practices correlate with negative financial consequences. For instance, Koskinen et al. (2024) reveal that high environmental performance correlates with improved profitability and valuations in U.S. firms, particularly those focused on shareholder interests. In contrast, Canadian firms demonstrate mixed financial results, revealing a nuanced balance between environmental and financial performance across varying governance structures. Furthermore, while a stakeholder-oriented focus can constrain financial gains from environmental efforts, a shareholder-centric approach may lead to adverse environmental repercussions. These insights have significant policy implications for advancing the broader dialogue on climate change reduction.

In summary, the gap in the current research lies in the need for a comprehensive understanding of how specific frameworks, such as the TCFD, moderate the relationship between CCE and financial outcomes, particularly in high-emission industries. While existing studies have established a positive relationship between ESG performance and

financial outcomes, more investigation needs to be worked into how the regulatory environment, especially the TCFD disclosures, influences this connection. Additionally, much of the research focuses on broad geographical areas or single risk dimensions (e.g., physical, transition, and regulatory risks) without exploring how these risks, when disclosed under a standard framework like TCFD, might impact financing access, capital costs, or market valuation for firms in high-emission industries.

Moreover, while the common-law vs. civil-law distinction in regulatory environments is discussed (e.g., La Porta et al. (1998) and Horváthová (2010)), further exploration is needed on how different legal and regulatory systems interact with ESG disclosures to mitigate or exacerbate climate risk impacts on financial performance, particularly for high-emission industries. The mixed results in studies like Koskinen et al. (2024), which observe varying outcomes across jurisdictions such as the U.S. and Canada, suggesting that contextual factors—including governance, legal structure, and climate-related policies—could be pivotal in shaping these relationships. Thus, a significant gap exists in studying the moderating role of TCFD disclosures in the relationship between high-emission industries' climate risk exposure and financial performance, especially in how global regulatory frameworks influence these firms' ability to manage climate risks and improve financial outcomes.

2.3 Hypotheses development

This hypothesis examines the impact of CCE on financial outcomes, specifically focusing on climate change exposures in high-emitting industries. By analyzing climate risks at the firm level based on (Sautner et al., 2023a), this study investigates both aspects of financial outcomes: how climate change exposure influences a firm's financial performance and default risk. According to Sautner et al. (2023b), firms in environmentally sensitive industries increasingly focus on the regulatory, opportunity, and physical risks of climate change. Chabot and Bertrand (2023) emphasize the need to tackle climate risks to maintain financial stability in the European financial system. Thus, if businesses can control climate risk exposure well, they can improve their ability to handle regulatory hurdles, prevent possible penalties, and strengthen their financial

security, ultimately bolstering their capacity to withstand market fluctuations driven by environmental conditions.

According to stakeholder theory, firms need to consider different stakeholders' concerns when making decisions to sustain long-term value (Freeman, 2010). A company's carbon emissions have a direct effect on its connections with stakeholders who are placing more importance on environmental accountability. Previous research has pointed out the impact of climate risk on financial results. For example, Matsumura et al. (2014) show that firms with higher carbon emissions have lower firm value, suggesting that the market punishes firms that neglect their environmental responsibilities. Their results emphasize how critical carbon disclosures are for demonstrating responsible environmental practices to investors. Continuing this investigation, Matsumura et al. (2024) explore the broader scope of climate risk's impact on various aspects of a company, showing that inadequately handling these risks leads to reduced company worth and increased risk, such as financial instability and market volatility. In a similar vein, Adamolekun and Kyiu (2024) corroborate the negative impact of carbon emissions on firm value, demonstrating that companies that decrease their carbon footprints during restructuring efforts receive better market valuations, aligning with (Perdichizzi et al., 2024). These results indicate that investors are increasingly favoring companies that proactively address climate risks, reducing the likelihood of experiencing financial difficulties in the future.

Previous empirical research indicates that climate risk significantly impacts firms' default risk, particularly stock market volatility. For instance, Aswani et al. (2024) discover that companies with higher carbon emissions meet increased market volatility and reduced stock returns as investors respond negatively to poor environmental practices. Bingler et al. (2024) illustrate that low climate disclosures heighten reputation risk and financial instability, whereas effective management of climate risks can lower firm risk and bolster investor confidence. Faccini et al. (2023) reveal that climate risks are progressively incorporated into stock prices, especially in sectors susceptible to regulatory and physical climate changes, resulting in increased financial risk and instability.

While previous research has explored the effects of climate change on financial outcomes, further examination is essential, mainly using firm-level data and global insights. First, this study uses CCE data from Sautner et al. (2023a). Concurrently, we also employ country-level information (the global climate performance index) sourced from Germanwatch to validate the findings. Second, earlier research primarily concentrates on the influence of climate performance indices on either financial performance or firm default risk. This study examines how climate change exposure affects financial performance and default risk. Also, existing studies often restrict their analysis to a specific country or region. This research provides global evidence, comparing firms in both high- and low-emission industries. It also investigates disparities between firms operating under common law and civil law systems, offering a more thorough understanding of climate risks and their financial implications. Based on the arguments for the connection between CCE and financial outcomes and the differences observed across various sectors and regulatory frameworks. Therefore, this study proposes the following hypothesis:

Hypothesis 1a: CCE adversely affects financial outcomes by increasing the likelihood of default and reducing firm value.

Hypothesis 1b: The negative relationship between CCE and firms' financial outcomes is more pronounced in high-emission sectors.

This hypothesis explores the impact of TCFD on the relationship between CCE and financial outcomes. The TCFD framework requires companies to disclose climate risks comprehensively, subjecting them to greater external scrutiny. Firms participating in the TCFD recommendation may strengthen positive signaling efforts, enhancing financial outcomes by improving credibility and stakeholders' trust (Dhaliwal et al., 2011; Plumlee et al., 2015). For instance, Matsumura et al. (2014) find that firms disclosing their carbon emissions reduces uncertainties related to climate risks and increase firm value, even when they have carbon liabilities, implying that companies joining the TCFD recommendations can reduce the financial impacts of carbon risks, which demonstrate a proactive approach to managing climate risks and meeting investor demands for

transparency. Similarly, Sautner et al. (2023b) find that firms with significant climate risks that produce high-quality climate disclosures, such as TCFD-aligned reports, are more effective in mitigating the financial effects of climate risks. These firms also lower their cost of capital by an average of 0.8% compared to those with poor disclosure practices.

According to previous studies, firms are affected by environmental disclosures in various ways, depending on the disclosure quality, the context, and the regulatory framework. Chen et al. (2018) finds that companies required to disclose CSR initiatives under China's 2008 policy experience lower profits but also contribute to positive environmental outcomes, such as reductions in industrial wastewater and CO₂ emissions. This suggests that mandatory CSR disclosures generate political and social pressure that shapes corporate behavior, driven more by external stakeholders than economic motives.

On the one hand, the non-financial disclosure can lead to negative financial outcomes. For example, Richardson and Welker (2001) find that social disclosures increase the cost of equity, thereby reducing firms' financial performance. In contrast, other studies highlight potential benefits. Dhaliwal et al. (2011) and Plumlee et al. (2015) find that firms with higher-quality voluntary ESG disclosures improve firm value by boosting future cash flows and lowering the cost of equity. Additionally, Aerts et al. (2008) and Matsumura et al. (2014) underscore the importance of accurate and reliable environmental reporting, strengthening stakeholders's trust, and improving analysts' earnings forecasts. Clarkson et al. (2013) argue that proactive environmental strategies and transparent reporting signal strong corporate commitment, positively influencing stock prices.

This study argues that companies implementing the TCFD framework are better positioned to mitigate the financial impact of climate risks, consistent with signaling and legitimacy theories. First, according to signaling theory, companies utilize disclosures to set themselves apart by indicating better environmental performance, ultimately obtaining a competitive edge (Clarkson et al., 2008). Clarkson et al. (2011) and Clarkson et al. (2008) suggest that firms with superior carbon performance reveal more measurable metrics to demonstrate their actions. Luo and Tang (2014) and Qian and Schaltegger (2017) emphasize that voluntary carbon disclosure reflects a company's commitment to

reducing climate risk and helps drive performance improvements. Second, legitimacy theory suggests that firms release environmental information to conform to societal norms and expectations, frequently to uphold societal approval (Gray et al., 1995; Patten, 2002; Perego & Kolk, 2012). Nonetheless, companies with subpar environmental performance might opt to make vague statements and symbolic disclosures instead of directly dealing with the root environmental problems (Cho et al., 2006; Dye, 1985; Hummel & Schlick, 2016). This approach can conceal subpar results while lessening external scrutiny (De Villiers & van Staden, 2006). Thus, this study hypothesizes:

Hypothesis 2: The negative association between CCE and financial outcomes is weakened for firms that join the TCFD.

3. Research design

3.1 Sample construction

This research employs a variety of data sources to investigate the correlation between CCE and financial outcomes. This study gathers insights on corporate default probabilities, the distance to default, and credit default swap information from the Risk Management Institute (RMI) at the National University of Singapore, utilizing the framework pioneered by Duan et al. (2012). Subsequently, this investigation collects firm-specific data from the LSEG Asset 4 database, including balance accounts, income statements, and environmental reporting. This study also sources firm-level climate risk exposure data from Sautner et al. (2023a). Last, GDP growth rates and institutional quality are obtained from the World Governance Indicators.

Following the integration of the databases mentioned above, we remove: 1) the financial industry and filters out any missing data in the estimation equations (103,402); 2) Observations without default probability data (6,917); 3) Data points without the necessary consistency measure for climate change exposures (5,349); 4) Companies are not merged with TCFD guidelines (3,513), and missing values from annual reports (1,684). In Table 1, the dataset comprises 6,229 companies (32,920 firm-year observations) across 48 countries from 2002 to 2021. All variables are trimmed at the standard 1st and 99th percentiles to minimize the influence of outliers.

[Insert Table 1 here]

3.2 Methodology

3.2.1 Empirical models and variable measurements

This study estimates the following equation (Eq. 1) to test the impact of CCE on firm value and default risk. We use panel data regression models to account for unobserved heterogeneity, improve estimation accuracy, and leverage cross-sectional and time-series dimensions. This approach can control for time-invariant characteristics, reducing omitted variable bias. The first hypothesis is validated when the β_1 coefficient is negative for firm value and positive for corporate default risk.

$$\begin{aligned} (\text{Financial outcomes})_{i,j,t} = & \beta_1 (CCE)_{i,j,t} + \beta_2 (TCFD)_{i,j,t} + \beta_3 (SIZE)_{i,j,t} + \beta_4 (AGE)_{i,j,t} + \beta_5 (CF)_{i,j,t} \\ & + \beta_6 (LEV)_{i,j,t} + \beta_7 (CAPE)_{i,j,t} + \beta_8 (PPE)_{i,j,t} + \beta_9 (GDP)_{j,t} + \beta_{10} (IQ)_{j,t} + \varepsilon_{i,j,t} \end{aligned} \quad (1)$$

In the firm-year panel data, i , j , and t represent firm i in country j at time t . Financial outcomes are evaluated using the firm's default risk and firm value (see Section 3.2.2 for detailed measurement definitions). The independent variable, firm-level climate risk exposure (CCE), is derived from the Bigram analysis of quarterly earnings conference calls, as constructed and provided by Sautner et al. (2023a). This variable has been widely known and applied in prior empirical studies (Agoraki et al., 2024; Ben-Amar et al., 2022; Hossain & Masum, 2022; Trinh et al., 2024).

This study incorporates relevant control variables, as emphasized in prior research (Alshahrani et al., 2023; Feng et al., 2024; Ferdous et al., 2024; Li et al., 2024; Trinh et al., 2024). The firm-level control variables include *TCFD*, firm size (*SIZE*), firm Age (*AGE*), Cash Flows (*CF*), Corporate Leverage (*LEV*), Capital Expenditure (*CAPE*), and Net Property, Plant, and Equipment (*PPE*). *TCFD* is a binary variable representing a company's support for the TCFD and its recommendations in year t . It equals one if the company declares support and zero otherwise. *SIZE* is calculated as the natural logarithm of the average total assets. Larger firms typically engage in more diverse business activities and exhibit more robust corporate governance, which can reduce business risk. *AGE* is measured as the natural logarithm of the years since the firm's listing. *CF* is calculated by operating cash flows divided by total book assets. *LEV* is calculated as the

ratio of total debt to total book assets. *CAPE* is determined by dividing total capital expenditure by the firm's sales revenue. Finally, *PPE* is property, plant, and equipment scaled by total book assets, as prior research (Huang et al., 2018; Trinh et al., 2024).

The country's characteristics include GDP growth rate (*GDP*) and Institutional quality (*IQ*). *GDP* serves as an economic indicator, representing the percentage change in the total economic output of a country over a defined period. *IQ* measures the quality of countries' institutional environments using six average indices: voice and accountability, political stability and absence of violence, rule of law, government effectiveness, control of corruption, and regulatory quality (Kaufmann et al., 2011). Regression models incorporate fixed effects for Year, Sector, and Country to control for unobserved characteristics. ε represents the error term.

This study also posits that the negative relationship between CCE and firms' financial outcomes is more pronounced for firms in high-emission sectors (H1b). We estimate the following equation (Eq. 2):

$$\begin{aligned} (\text{Financial outcomes})_{i,j,t} = & \beta_1 (\text{CCE})_{i,j,t} + \beta_2 (\text{High Emission})_{i,j,t} + \beta_3 (\text{CCE} \times \text{High Emission})_{i,j,t} + \beta_3 (\text{SIZE})_{i,j,t} \\ & + \beta_4 (\text{AGE})_{i,j,t} + \beta_5 (\text{CF})_{i,j,t} + \beta_6 (\text{LEV})_{i,j,t} + \beta_7 (\text{CAPE})_{i,j,t} + \beta_8 (\text{PPE})_{i,j,t} + \beta_9 (\text{GDP})_{j,t} \\ & + \beta_{10} (\text{IQ})_{j,t} + \varepsilon_{i,j,t} \end{aligned} \quad (2)$$

This study further investigates the joint effect of CCE and TCFD on firm' financial outcomes; We estimate the following equation (Eq. 3):

$$\begin{aligned} (\text{Financial outcomes})_{i,j,t} = & \beta_1 (\text{CCE})_{i,j,t} + \beta_2 (\text{TCFD})_{i,j,t} + \beta_3 (\text{CCE} \times \text{TCFD})_{i,j,t} + \beta_3 (\text{SIZE})_{i,j,t} \\ & + \beta_4 (\text{AGE})_{i,j,t} + \beta_5 (\text{CF})_{i,j,t} + \beta_6 (\text{LEV})_{i,j,t} + \beta_7 (\text{CAPE})_{i,j,t} + \beta_8 (\text{PPE})_{i,j,t} \\ & + \beta_9 (\text{GDP})_{j,t} + \beta_{10} (\text{IQ})_{j,t} + \varepsilon_{i,j,t} \end{aligned} \quad (3)$$

Where Financial outcomes are evaluated using the firm's default risk and firm value (see Section 3.2.2 for detailed measurement definitions). The relationship between CCE and TCFD underscores that firms aligned with TCFD guidelines actively engage in assessing climate-related risks and opportunities. Furthermore, these companies are committed to disseminating climate-related information in line with TCFD's reporting standards, enhancing transparency by providing market stakeholders with climate-

focused information, and enabling informed decision-making regarding climate impacts on financial performance. Consequently, this research expects a reduction in the negative impact of climate change on financial outcomes for firms participating in TCFD, consistent with Hypothesis 2. Details of all control variables are provided in Appendix A1

3.2.2 Variable measurements

Dependent variable

The following dependent variable, DTD (default distance), is a proxy for firm default risk (Equation 4). DTD provides a standardized measure of how close or far a firm is from default, with higher values indicating a lower probability of default. Structural models of Merton (1974) and Leland (1994) conceptualize the market value of a firm's assets as a call option on the firm's unleveraged assets, with the firm's liabilities as the strike price. Duan et al. (2012) adjust to their DTD calculation to address structural model limitations. Duan et al. (2012) refine their DTD calculation by integrating the forward intensity model with a reduced-form DTD approach, enabling the generation of forward-looking PD term structures using dynamic macro-financial and firm-specific data. This enhanced framework incorporates more comprehensive information compared to classic structural models, such as Merton (1974), offering improved accuracy in default risk assessment.

$$DTD_t = \frac{\text{Ln}\left(\frac{V_t}{F + \delta \cdot L}\right) + \left(\mu_v - \frac{\xi_v^2}{2}\right)\tau}{\xi_v \sqrt{\tau}} \quad (4)$$

Where V is the market value of the firm's assets at time t ; F represents the firm's debt at time t (typically proxied by short-term and a portion of long-term liabilities); L is additional liabilities or obligations not captured in F . δ : a fraction adjusting the contribution of the additional liabilities to the default point; μ_v Expected return on the firm's assets (drift term). ξ Volatility of the firm's assets, reflecting uncertainty in asset values. τ time horizon over which default risk is evaluated. The details can refer to Duffie et al. (2007) and Duan et al. (2012).

To measure default risk, this study employs the probability of default (PD) developed by Duan et al. (2012), following prior studies such as Shih et al. (2021). This approach integrates elements of both reduced-form and structural models. In this study, the probability of default is measured for time frames ranging from 1 to 24 months, using data from RMI at the National University of Singapore. The PD is calculated as (Equation 5):

$$PD = \phi(-DTD) \quad (5)$$

Where, the standard normal distribution's cumulative distribution function is denoted by ϕ . The inverse of the normal distribution can be leveraged to represent the DTD as a function of the probability of default.

This study measures firm value using *Tobin's Q* and *ROA* (Agoraki et al., 2024; Albuquerque et al., 2018; Chen et al., 2018). Tobin's Q is calculated by adding the market value of equity, total debt (both long- and short-term), and the liquidation value of preferred stocks, then dividing by the book value of total assets. *ROA* is calculated as earnings before interest, taxes, depreciation, and amortization (*EBITDA*) divided by total book assets.

Independent variable

The climate risk index, created by Sautner et al. (2023a), measures firm-level exposure to climate risks through communication content, showing significant variations across firms and time. The CCE variable integrates risks arising from regulatory, physical, and transitional climate change impacts. This index addresses different types of firm-level climate risks, is developed similarly to the political risk metric by Hassan et al. (2019), using bigram analyses to track relevant keywords like climate risk and climate risk uncertainty. The index also correlates positively with alternative indicators, such as the carbon footprint index by Engle et al. (2020). A firm with high CCE, value indicates more significant exposure to climate risks related to opportunities, regulations, and physical shocks.

3.3 Descriptive statistic

Panel A of Table 2 analyses the distribution of companies categorized by their Global Industry Classification Standard (GICs) codes. The largest industry group is Industrials (22.46%), followed by materials (11.64%) and consumer discretionary (13.95%). These three industries account for nearly half (48.05%) of the sample. Other sectors such as health care, information technology, and communication services are also featured, contributing approximately 9-10%. Smaller sectors include utilities (5.40%) and energy (5.50%). The final dataset comprises 32,920 observations, fully distributed across all industries, ensuring comprehensive coverage of different sectors.

Table 2, Panel B, reports a substantial rise in observations, expanding from 54 in 2002 to 5,983 in 2021, driven by the increasing availability of climate change exposure data from Sautner et al. (2023a) and financial data from LSEG Thomson Reuters Eikon. Panel C also shows that firms from the United States (9,696), Japan (3,636), and the United Kingdom (2,696) contribute substantially, making up 49% of the total observations. In contrast, Monaco, Panama, Malaysia, and Uruguay firms have the fewest observations, representing just 3.33% of the sample.

[Insert Table 2 here]

Panel A of Table 3 presents the summary statistics for the regression variables. The mean *CCE* is 1.431 (Std. Dev=2.567), with a percentile range of 0.173 to 6.803. Furthermore, Fig. 2 and 3 illustrate that most firms actively adopting the TCFD program from 2002 to 2021 exhibit significantly lower levels of climate risk exposure than those not participating. In terms of financial outcomes, the mean probability of default (*PD-Im*) and corporate credit default swap (*CDS*) in the sample are 0.0225 (Std. Dev=0.2108) and 18.089 (Std. Dev=38.721), respectively. In addition, the firm's growth opportunities (*Tobin's Q*) and net income over its total assets (*ROA*) have mean values of 1.653 (median=1.132) and 0.032 (median=0.040), respectively. The average firm size is 4.719 (median=4.793), while leverage averages 0.283 (median=0.265). Furthermore, the average cash flow is 0.009 (Std. Dev=0.086), and capital expenditure (*CAPE*) averages 0.049 (Std. Dev=0.045). The average *PPE* ratio is 0.418. Lastly, regarding the country characteristics, the mean values of *GDP* and *IQ* in the sample are approximately 2.088

(median=2.251) and 1.020 (median=1.242), respectively. We provide the definitions and the correlation matrix for all variables in Appendix A1.

[Insert Table 3 here]

Panel B of Table 3 reports the results of the univariate tests. This table compares financial outcome measures, *CCE*, and control variables between two subsamples: firms operating in high-emitting industries and those in low-emitting industries. The findings indicate that high-emitting firms exhibit a higher probability of default, lower distance to default, and lower values of *Tobin's Q* and *ROA* than their low-emitting counterparts. The differences in financial outcomes (*PDs*, *CDS*, *DTD*, *Tobin's Q*, and *ROA*) between the subsamples are statistically significant at the 1% level. The findings indicate that high-emitting firms have significantly higher values for *CCE*, *OPE*, *CO₂*, and *TCFD* than low-emitting firms. The average *CCE* is 2.8831 for high-emitting firms versus 0.6580 for low-emitting firms, a difference of 2.2250 significant at the 1% level. *CO₂* is more significant, with averages of 6,932,728 metric tons for high-emitting firms and 714,727 metric tons for low-emitting firms, differing by 6,218,001 metric tons (See Fig. 4). Lastly, high-emitting firms report higher *TCFD* disclosure levels, averaging 0.2003 compared to 0.1409, a statistically significant difference of 0.0595. While these findings give early support for the hypothesis, the considerable disparities in firm characteristics between the two subsamples highlight the need to control for these aspects in our multivariate analysis.

4. Baseline regression results

4.1 The effect of CCE on financial outcomes (firm default risk and value)

Panel A of Table 4 presents the empirical results from the panel data regression models. The dependent variables in this analysis are the probability of default within one month (*PD-1m*) for models (1)–(4) and credit default swap spreads (*CDS*) for models (5)–(8). The analysis begins with a baseline model model (1) that excludes control variables. Subsequently, three alternative models are estimated: Model (2) incorporates additional control variables, model (3) adds control variables and *TCFD* to assess the direction of their effect, and Model (4) includes controls for mandatory climate-related disclosure

requirements at the firm level. Models (5)–(8) use the same modeling approach with the alternative dependent variable, CDS.

The first hypothesis expects the adverse effects of CCE on financial outcomes by increasing the likelihood of default and reducing firm value. The estimated coefficients for CCE are 0.389, 0.323, and 0.117 in models (1), (2), and (4), respectively, all statistically significant at the 1% level ($p < 0.01$). From an economic perspective, a 1% increase in CCE corresponds to a 0.389% rise in corporate default risk, as shown in model (1), reflecting the overall effect of CCE. The results are robust, with more significant impacts observed across all models. In addition, Panel B of Table 4 presents the results using Tobin's Q (models 9–12) and ROA (models 13–16) as dependent variables. The findings confirm hypothesis 1, as evidenced by the significant negative coefficients for CCE: -0.170 , -0.093 , and -0.761 ($p < 0.01$ in models (9), (10), and (12)). From an economic perspective, a 1% increase in CCE leads to a 0.170% decline in firm value, as specified in Equation (1). This negative association is reliable and holds consistently across alternative firm performance measures, including ROA, as shown in models (13)–(16).

The findings indicate that high corporate exposure to climate change results in significantly higher default risk and reduced firm value, confirming previous research (Feng et al., 2024; Matsumura et al., 2014, 2024; Sun et al., 2024). These results align with legitimacy theory, suggesting that failing to address environmental issues can undermine a firm's credibility, leading to decreased investor confidence, higher financing costs, and resource constraints, thereby exacerbating financial vulnerabilities. Additionally, the results support stakeholder theory, emphasizing the importance of addressing key stakeholder concerns. Firms that fail to manage climate risks in line with stakeholder expectations risk reputational damage, regulatory penalties, and reduced market support, ultimately heightening financial instability and default risk. These findings underscore the critical need for firms to implement effective climate risk management strategies to protect their reputation, meet stakeholder demands, and reduce the likelihood of default.

[Insert panel A of Table 4 here]

4.2 The joint effects of TCFD and CCE on financial outcomes

Consistent with the second hypothesis, firms participating in the TCFD framework mitigate the negative impact of CCE on financial performance. This is evidenced by the significant negative coefficients of the interaction term (TCFD×CCE) on firm default risk ($b=-2.894$ and -1.758 ; $p < 0.01$ in models (4) and (8), Panel A) and the significant positive coefficients on firm value ($b=1.561$ and 1.123 ; $p < 0.05$ in models (12) and (16), Panel B). These findings indicate that firms adopting the TCFD framework are more effective at mitigating the adverse effects of CCE on financial outcomes, supporting both signaling theory and legitimacy theory.

According to signaling theory, firms adopting the TCFD framework send a credible signal to stakeholders about their commitment to managing climate-related challenges effectively. By providing transparent and forward-looking climate disclosures, these firms differentiate themselves as better prepared to navigate climate risks, thereby enhancing stakeholder confidence and reducing perceived risk. From the legitimacy theory perspective, adherence to the TCFD framework reflects a proactive effort by firms to align with societal norms and expectations regarding climate responsibility. Such alignment reinforces the firm's legitimacy, which can attract greater stakeholder support, reduce external scrutiny, and enhance financial stability. The results imply that participation in the TCFD framework is an effective mechanism for firms to address climate-related challenges, reduce default risk, and maintain stakeholder trust, highlighting the strategic importance of transparent climate risk disclosure in strengthening financial resilience.

The results show that firms adopting the TCFD framework benefit from improved financial performance, reflected in higher Tobin's Q and ROA. Specifically, the positive coefficients for TCFD in Models 11 and 12 ($b=2.313$ and 5.052 , Panel B, respectively) indicate that TCFD participation is linked to increased firm value and profitability. This implies that firms with higher climate risk exposure, which also participate in the TCFD framework, experience less severe negative impacts on their firm value and profitability. By adopting the TCFD framework, firms can signal to stakeholders their commitment to

addressing climate risks, thereby reducing the adverse financial effects of climate exposure and enhancing their overall financial stability.

[Insert panel B of Table 4 here]

4.3 The effect of CCE on firm financial outcomes in environmentally sensitive sectors

So far, this study divides the sample based on the TCFD classification to test hypothesis H1b. The TCFD framework recognizes that specific industries are more exposed to financial risks due to their involvement in transition and physical risks linked to their operations and products. The TCFD classifies industrials, energy, utilities, and materials as high-carbon industries, in contrast to low-carbon sectors such as consumer discretionary, consumer staples, healthcare, and telecommunications (TCFD, 2017). The variable High Emission is a dummy that equals one for carbon-intensive firms and zero otherwise, following prior study (Kabir et al., 2021). This study expects that the interaction term (*CCE×High Emission*) positively affects firms' default risk and negatively affects firms' value.

In Panel C of Table 4, the findings reveal a positive relationship between the interaction variables and firms' default risk, along with a negative impact on firm value, indicating that firms in highly polluting industries face greater default risk. Also, the interaction terms show higher coefficients compared to the individual carbon emission variables. For instance, *CCE×High Emission* coefficients are -0.023 and -0.105 , compared to CCE coefficients of -0.099 and -0.150 (as shown in models 3-4). These findings align with Jung et al. (2018) and Kabir et al. (2021), which suggest that firms in high-emitting industries are at a higher risk of default due to increased carbon emissions than those in low-emitting industries.

[Insert panel C of Table 4 here]

5. Endogeneity issues

This section uses PSM to handle endogeneity due to observable self-selection bias as noted by Alshahrani et al. (2023) and Roberts and Whited (2013). This approach validates consistent findings regardless of the estimation technique used, thus preventing

endogeneity problems such as omitted variable bias and reverse causality. This analysis defines the treatment group as firms exhibiting elevated climate change exposure and the control group as those demonstrating minimal climate-related risk vulnerabilities. This analysis categorizes firms based on their climate exposures: those above the sample median are classified as high climate change firms. In contrast, those below the median are classified as low climate change firms. A set of covariates comprising *SIZE*, *AGE*, *CF*, *LEV*, *CAPE*, *PPE*, *GDP*, and *IQ* are considered in the analysis. The nearest neighbor matching technique is employed to identify a subset of firms characterized by similar propensity matching scores to those of the control group.

In this context, logistic regression employing a binary dependent variable is utilized within a two-stage estimation framework, and a caliper matching method with a 1% caliper is implemented. The subsequent second-stage model is conducted using OLS regression, with an analysis sample size of 36,956, and employs the matched observations within the panel. In the first logistic regression, the outcomes presented in Table 5, Panel A display a strong positive relationship between high climate change exposure firms and factors such as *SIZE*, *AGE*, and *PPE*. On the other hand, *CF* and *IQ* have a significant negative impact on companies' probability of high climate change exposure. Moreover, *LEV*, *CAPE*, and *GDP* coefficients are not statistically significant.

Panel B presents a comparative analysis of the mean values between the treatment and control groups, employing the same control variables utilized in Panel A (refer to Table 5 for details). It also reports t-statistics for firm characteristics related to these control variables. Panel B shows no significant differences between the groups, except for the *CAPE*, which is significant at the 10% level. In sum, the univariate comparisons suggest that the matching process successfully eliminated noticeable differences between the control and treatment groups, except for those associated with climate risk exposure.

Panels (C) and (D) provide compelling evidence from the second-stage regression results for the PSM sample. The *CCE* positively affects firm default risk (as shown in Models 1-8 of Panel C) and negatively affects firm value (as shown in Models 9-12 of Panel D). These results reinforce the baseline analysis (H1a). Firms with higher exposure

to climate-related risks are more susceptible to financial instability, thereby increasing their likelihood of default.

The test finds that the adverse effects of CCE on financial outcomes is more pronounced for firms participating in the TCFD framework. This result is consistent with hypothesis H2. Specifically, the significant negative $TCFD \times CCE$ coefficients are -2.536 and -2.094 , respectively (as shown in Models 4 and 8, Panel C), while the positive coefficients are 1.123 and 2.611 , respectively (as shown in Models 12 and 16, Panel D). These findings are consistent with the benchmark analysis, even when employing the PSM sample.

[Insert Table 5 here]

6. Robustness test

This section validates the baseline findings through rigorous robustness checks. These tests include using alternative measurements of climate change exposure (Table 6), testing with different firm default risk measures (Table 7 and 8), and excluding U.S. firms from the sample (Table 9).

6.1 Alternative climate change exposure

Table 6 presents the empirical tests for firm default risk models (1)-(6) and firm value models (7)-(12). The independent variable, CO_2 , represents carbon emissions measured in thousands of metric tons. This study reveals a negative relationship with financial outcomes, supporting the baseline model and aligning with Matsumura et al. (2014) and Ferdous et al. (2024). The coefficients of the CO_2 variable show a significant negative association, with values of $b = -0.793$ and $b = -0.260$ ($p < 0.01$) in models (9) and (12), respectively. This result confirms Hypothesis (H1a). Economically, this indicates that for every additional unit of carbon emissions, the firm value decreases by approximately 0.793 and 0.260 units, respectively, highlighting the financial penalties associated with higher carbon footprints. The coefficients for CO_2 in models (3)–(6) confirm the expected signs, indicating that companies with elevated carbon emissions face a greater default risk, with coefficients of 0.526 and 0.485, respectively. Moreover,

companies adopting TCFD reporting can lessen the adverse effects of CO2 on their financial results, which is consistent with the baseline models.

[Insert Table 6 here]

6.2 Alternative measure of firm's default risk

This test incorporates alternative measurements to strengthen the clarity and robustness of the baseline analysis. The dependent variables include *DTD*, *PD-3m*, and *PD-6m* (models 1–9, Panel A), as well as *PD-1Y* and *PD-2Y* (models 10–15, Panel B). Appendix A1 provides a detailed description of the variable measurements, while Panels A and B in Table 7 and Table 8 present the empirical results. The findings reveal a consistent positive relationship between CCE and firms' default risk across all models. These findings reinforce that climate risks—physical (such as catastrophic weather events) and transitional (like regulatory changes)—pose significant dangers to a firm's financial stability. Interestingly, this analysis also finds that CCE is correlated with decreased default risk for firms participating in the TCFD framework, consistent with the baseline results. These findings suggest that firms adopting the TCFD framework tend to have more robust governance practices and effective risk management systems to address climate-related challenges. This proactive approach enables them to mitigate the negative financial impacts of climate risks.

[Insert Table 7 and Table 8 here]

Financial Constraints Proxies: Kaplan-Zingales and Whited-Wu Indices

Firms with different levels of financial constraints are likely to respond differently to climate change exposure risks. The Kaplan and Zingales (KZ) index (Kaplan & Zingales, 1997) and the Whited and Wu (WW) index (Whited & Wu, 2006) are commonly used proxies for financial constraints, measuring the degree of financial constraints by evaluating factors such as cash flow, leverage, and investment opportunities (Bai et al., 2022; Zhang, 2022). Return on equity (*ROE*), a key profitability indicator, also reflects how efficiently a firm generates shareholder equity returns.

This study uses these indices in the analysis to strengthen the robustness of the baseline model. Specifically, they help address potential endogeneity or omitted variable

bias associated with financial health, ensuring that the estimated effects of climate change exposure on financial outcomes are not confounded by unobservable factors related to firms' financial constraints. The findings show that firm-level climate change exposure increases financial constraints (as measured by the KZ and WW indices) and decreases firm value (as indicated by ROE), which aligns with the baseline models. These results suggest that climate change exposure exacerbates financial constraints by introducing higher uncertainty and potential costs related to regulatory changes, physical impacts, and market shifts.

Furthermore, the interaction term ($TCFD \times CCE$) reduces financial constraints (KZ and WW indices) and increases ROE, which is consistent with the baseline models. These findings suggest that the TCFD framework enhances transparency, enabling better risk management and stakeholder engagement. As a result, TCFD adoption can alleviate financial constraints linked to climate change exposure, improving firms' financial stability and long-term performance.

[Insert Panel C of Table 8 here]

6.3 Exclusion of firms operating in the United States (U.S.)

Since U.S. firms represent the most significant portion of the sample in this research, the study excludes U.S. firms when re-estimating all models to address potential concerns about the dominance of countries with disproportionately large numbers of observations. As shown in Table 9, firms participating in the TCFD framework negatively moderate the adverse effects of CCE on financial outcomes. Specifically, the significant negative coefficients for firm default risk ($TCFD \times CCE = -3.377, -1.803$; $p < 0.01$ in models 4 and 8) and the significant positive coefficients for firm value ($TCFD \times CCE = 1.122, 5.174$; $p < 0.05$ in models 12 and 16) suggest that the TCFD framework helps mitigate the adverse effects of climate change exposure on firm performance. Overall, the findings remain robust and consistent.

[Insert Table 9 here]

6.4 Legal framework environment (common law and civil law)

This subsection explores the impact of varying legal frameworks—common law and civil law—on the interplay between CCE and a firm's financial performance. This categorization is the principal empirical metric for assessing institutional variances across nations, in line with methodologies commonly employed in the existing literature (Ferdous et al., 2024; La Porta et al., 1998). Separate regressions are conducted for each subsample, focusing on CCE, TCFD, and their interaction term ($TCFD \times CCE$) as predictors of firm default risk while controlling for industry, country, and year-fixed effects.

Panels A to D of Table 10 show that CCE is significantly positively related to firms' default risk and negatively related to firm value in civil law countries. In contrast, the findings for firms in common law countries differ from the baseline models. For example, in Panel A, the coefficients for climate change exposure in common law countries are insignificant, with values of 0.411, 0.298, and 0.593 ($p\text{-value} > 0.1$ in Models 1, 2, and 4). Moreover, this study finds that the negative relationship between firm-level climate change exposure and firm value and the positive relationship with default risk is more pronounced for firms participating in the TCFD framework. These effects are more consistent and significant for firms in civil law countries compared to those in common law countries. For instance, in Panel A, the interaction term $TCFD \times CCE$ shows an insignificant coefficient in common law countries (-0.984, $p\text{-value} > 0.1$, Model 4). In contrast, it exhibits a significantly negative coefficient in civil law countries (1.391, $p\text{-value} < 0.01$, Model 8). The findings show that companies implementing the TCFD framework more effectively mitigate the adverse effects of climate risk on financial outcomes, which is pronounced for firms in civil law countries than in common law countries.

This study aligns with previous research by La Porta et al. (1998), suggesting that firms in civil law countries, which typically have more prescriptive regulations and fewer market-driven mechanisms than common law countries, tend to benefit more from participating in the TCFD framework. This highlights the importance of developing targeted strategies to promote TCFD adoption, especially in regions where legal and

regulatory systems may influence the effectiveness of climate risk management. For firms in common law countries, the lack of a significant impact from TCFD participation may indicate the need for additional measures, such as stronger market incentives or more robust regulatory guidance, to realize the potential benefits of the framework.

[Insert Table 10 here]

7. Conclusion

This study examines the relationship between CCE and corporate financial outcomes, including firm default risk and value, focusing on high-emission sectors and the moderating effect of firms adopting TCFD recommendations. The key findings of this study include. First, we find that firm-level risk of climate change significantly increases firm default risk and reduces firm value, particularly for firms with high carbon emissions. This confirms the vulnerability of carbon-intensive firms to climate-related financial risks, reinforcing prior studies that suggest the importance of addressing environmental risks in corporate strategy and market valuation (Adamolekun & Kyiu, 2024; Matsumura et al., 2014, 2024). Second, this analysis reveals that firms participating in TCFD disclosures experience a reduction in the positive relationship between CCE and firm default risk. This highlights the crucial moderating role of standardized climate disclosures in enhancing transparency and mitigating the financial impacts of climate risk.

Furthermore, the study finds that the relationship between CCE and financial performance differs significantly between firms in common law and civil law jurisdictions. The moderating effect of TCFD disclosure is more pronounced for firms in civil law countries, where high CCE is more strongly associated with financial constraints and reduced firm value. In contrast, the relationship is weaker for firms in common law countries, and TCFD participation does not appear to reduce the financial risks associated with climate exposure significantly. Lastly, by addressing the endogeneity issue through the use of PSM, this study provides more robust and credible results, enhancing the findings' reliability and contributing to the growing body of literature on corporate sustainability.

From a theoretical perspective, this study makes several contributions. It extends stakeholder and signaling theories by illustrating how climate-related disclosures,

particularly those following TCFD guidelines, can signal stakeholders regarding a firm's proactive approach to managing climate-related risks. Furthermore, this study contributes to the literature on corporate environmental disclosure frameworks, emphasizing the role of TCFD in reducing inconsistencies in climate-related information and improving decision-making. The research also addresses the heterogeneity in climate risk exposure among firms, showing that high-carbon-emission firms are more vulnerable to climate risks, a gap in prior research that generalized climate risks across industries. The findings offer significant insights for stakeholders such as managers, investors, and policymakers. For managers, adopting TCFD disclosures can serve as a strategic approach to effectively manage climate change risks and mitigate the company's exposure to financial instability. For investors, the study underscores the importance of considering TCFD participation as an indicator of a firm's ability to navigate climate risks, thus improving investment decisions. Policymakers can use the study's findings to promote or mandate TCFD disclosures, creating a more transparent and resilient corporate environment. Finally, high-carbon-emission firms are encouraged to enhance their climate-related disclosures as part of a broader strategy to improve their reputation, manage risk, and safeguard long-term financial performance.

In conclusion, this study offers valuable insights into the relationship between CCE, firm performance, and climate-related disclosures. The findings suggest that firms adopting TCFD disclosures, especially in civil law countries, are better equipped to manage climate risks. This emphasizes the importance of considering legal framework differences when evaluating climate change risk and the effectiveness of such TCFD in mitigating the adverse effect of CCE on firm financial outcomes. This research contributes to the ongoing dialogue on the role of corporate climate risk management in enhancing firm resilience and investor confidence, offering important implications for managers, investors, and policymakers in both developed and emerging markets. Despite its contributions, this study has several limitations. The study focuses primarily on the TCFD framework but does not compare its effectiveness to other climate disclosure frameworks. Future research could expand by examining the comparative effectiveness of TCFD and other frameworks, such as those from regional or industry-specific regulators, in mitigating financial risks associated with climate exposure. Furthermore,

the study's focus on common law and civil law countries offers a broad understanding of the impact of legal frameworks. Still, it may not fully capture the nuances of other legal systems, such as those in mixed jurisdictions or emerging markets. Future studies could investigate the role of different legal systems and their impact on climate risk disclosures and financial outcomes.

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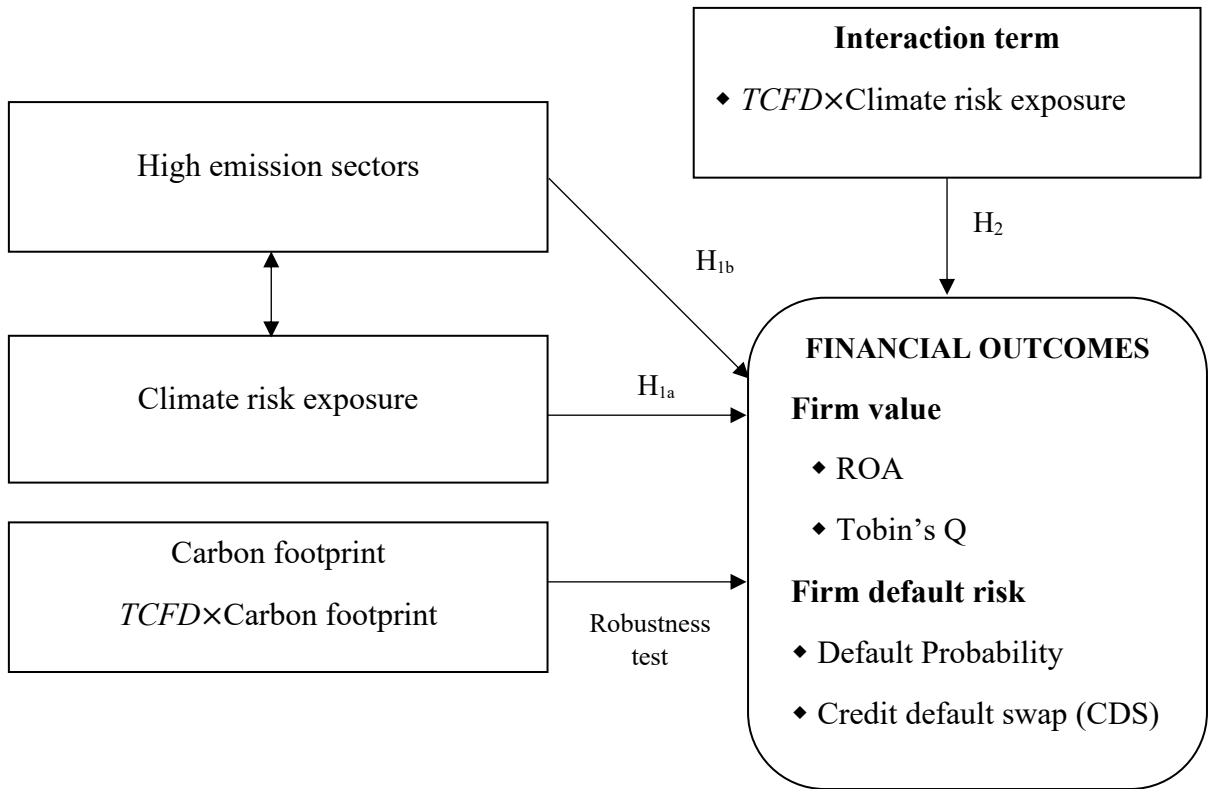


Figure 1: Conceptual framework

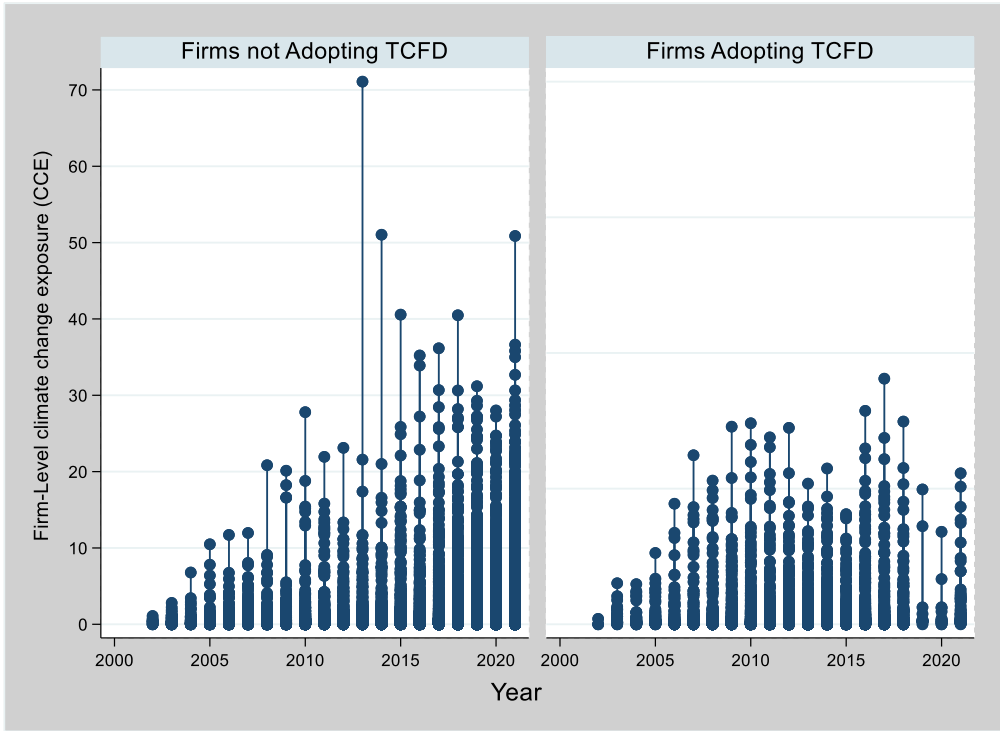


Figure 2: Two decades trends in climate change exposure risk: TCFD-adopting vs. non-adopting firms

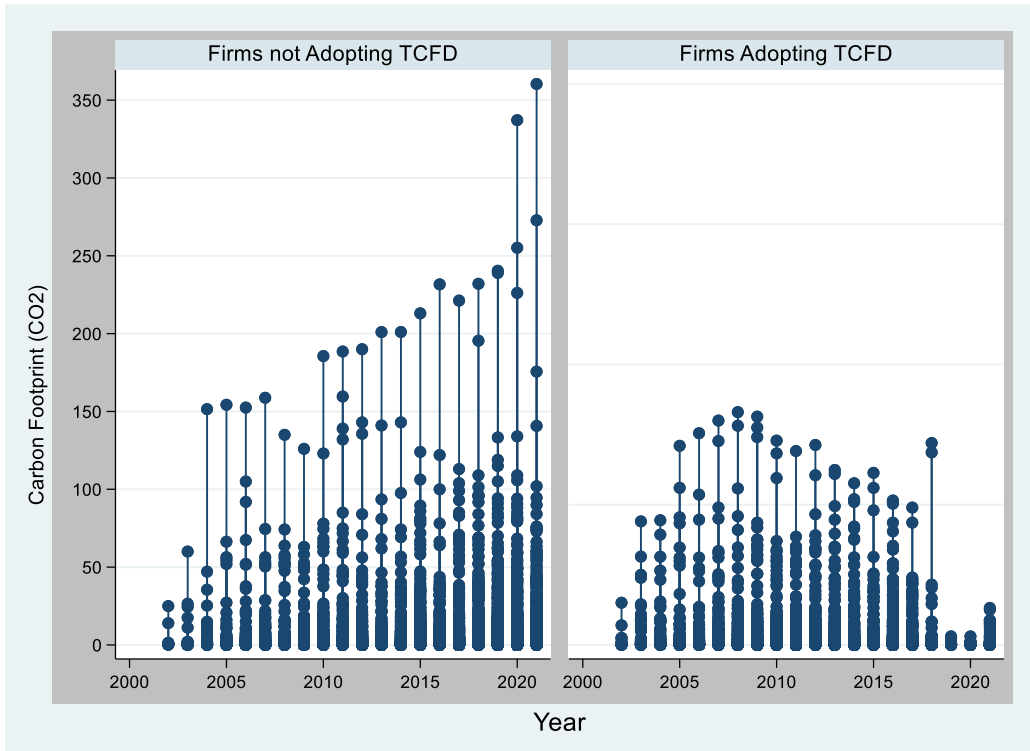


Figure 3: Two decades trends in carbon footprint (CO₂): TCFD-adopting vs. non-adopting firms

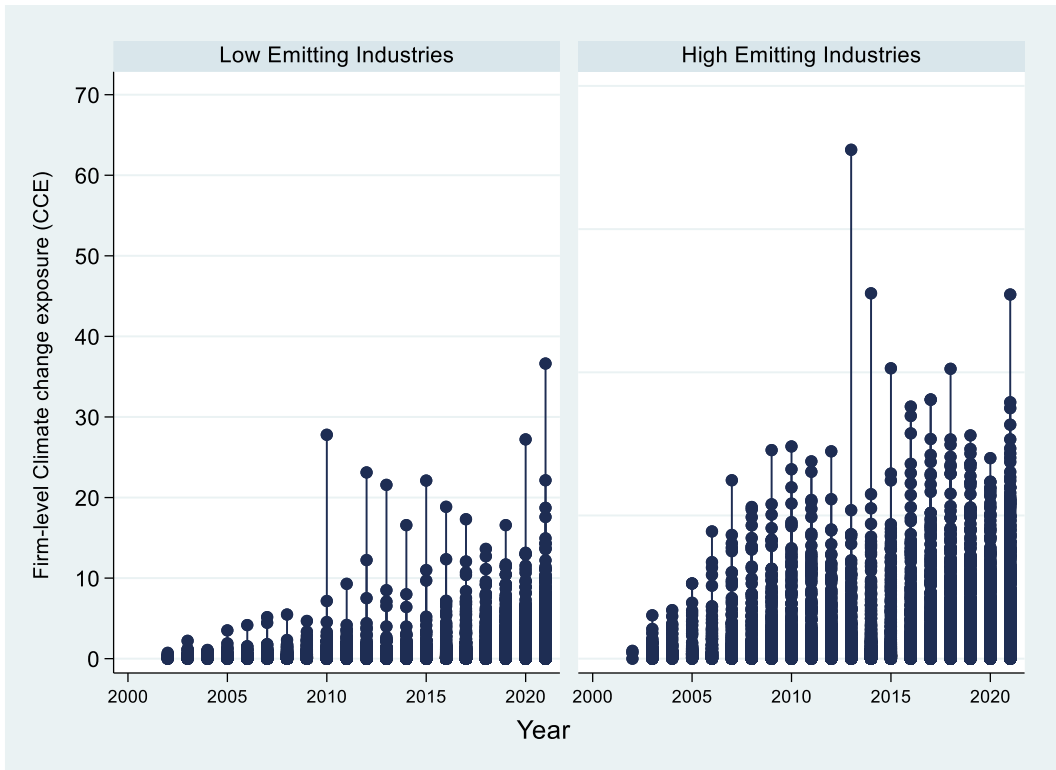


Figure 4: Trends in carbon footprint over two decades: High- vs. Low-emission industries

Table 1: Sample selection criteria

| Description | Firm-year obs. |
|--|-----------------------|
| Observations from the Thomson Reuters and Eikons database, 2002-2021 | 153,785 |
| <i>Less:</i> | |
| <i>Observations attributed to financial firms</i> | 103,402 |
| <i>Observations with missing default probability data</i> | 6,917 |
| <i>Observations with missing data for the measure of consistency in climate change exposures</i> | 5,349 |
| <i>Annual report information is not available in Perfect Information</i> | 1,684 |
| <i>Firms not matched with TCFD</i> | 3,513 |
| Final balanced sample | 32,920 |

Table 1 presents the sample selection criteria for this study. To ensure data accuracy, we select only companies with complete information on default probability, distance to default, earnings, revenue, and total book asset value for at least four consecutive years. Past research recognizes the unique features of the financial sector (Agoraki, 2024). Following Sun (2024) and Agoraki (2024), this study excludes financial companies from the sample (103,402), removes observations without default probability data (6,917), and omits records lacking consistency in climate change exposure (5,349). It also excludes missing values from annual reports (1,684) and firms not matched with TCFD (3,513). The final dataset comprises 6,229 companies with 32,920 yearly observations across 48 countries from 2002 to 2021. Each variable is winsorized at the 1st and 99th percentiles to reduce the potential impact of outliers.

Table 2: Sample distribution*Panel A: Distribution of samples by industry*

| GICs Code | Industry classifications | Frequency | Percent (%) | Accumulation percentage (%) |
|------------------|---------------------------------|------------------|--------------------|------------------------------------|
| 10 | Energy | 1,810 | 5.498 | 5.498 |
| 15 | Materials | 3,833 | 11.643 | 17.141 |
| 20 | Industrials | 7,392 | 22.455 | 39.596 |
| 25 | Consumer Discretionary | 4,592 | 13.949 | 53.545 |
| 30 | Consumer Staples | 2,848 | 8.651 | 62.196 |
| 35 | Health Care | 3,163 | 9.608 | 71.804 |
| 45 | Information Technology | 3,138 | 9.532 | 81.336 |
| 50 | Communication Services | 1,977 | 6.006 | 87.342 |
| 55 | Utilities | 1,776 | 5.395 | 92.737 |
| 60 | Real Estate | 2,391 | 7.263 | 100.000 |
| Total | | 32,920 | 100 | |

Panel B: Distribution of samples by year

| Year | Frequency | Percent (%) | Accumulation percentage (%) |
|--------------|------------------|--------------------|------------------------------------|
| 2002 | 54 | 0.164 | 0.164 |
| 2003 | 135 | 0.410 | 0.574 |
| 2004 | 210 | 0.638 | 1.212 |
| 2005 | 330 | 1.002 | 2.214 |
| 2006 | 442 | 1.343 | 3.557 |
| 2007 | 531 | 1.613 | 5.170 |
| 2008 | 602 | 1.829 | 6.999 |
| 2009 | 752 | 2.284 | 9.283 |
| 2010 | 957 | 2.907 | 12.190 |
| 2011 | 1,146 | 3.481 | 15.671 |
| 2012 | 1,222 | 3.712 | 19.383 |
| 2013 | 1,284 | 3.900 | 23.283 |
| 2014 | 1,344 | 4.083 | 27.366 |
| 2015 | 1,488 | 4.520 | 31.886 |
| 2016 | 1,738 | 5.280 | 37.166 |
| 2017 | 2,156 | 6.549 | 43.715 |
| 2018 | 2,986 | 9.070 | 52.785 |
| 2019 | 4,308 | 13.086 | 65.871 |
| 2020 | 5,252 | 15.954 | 81.825 |
| 2021 | 5,983 | 18.175 | 100.000 |
| Total | 32,920 | 100.000 | |

Panel C: Distribution of samples by country

| Country | Frequency | Percent (%) | Accumulation percentage (%) | Country | Frequency | Percent (%) | Accumulation percentage (%) |
|----------------|-----------|-------------|-----------------------------|--------------|---------------|---------------|-----------------------------|
| Monaco | 11 | 0.033 | 0.033 | Chile | 197 | 0.598 | 5.854 |
| Panama | 11 | 0.033 | 0.066 | Malaysia | 209 | 0.635 | 6.489 |
| Uruguay | 11 | 0.033 | 0.099 | Singapore | 241 | 0.732 | 7.221 |
| Vietnam | 12 | 0.036 | 0.135 | New Zealand | 264 | 0.802 | 8.023 |
| Morocco | 18 | 0.055 | 0.190 | Mexico | 292 | 0.887 | 8.910 |
| Poland | 18 | 0.055 | 0.245 | Ireland | 297 | 0.902 | 9.812 |
| Hungary | 20 | 0.061 | 0.306 | Norway | 307 | 0.933 | 10.745 |
| Cayman Islands | 29 | 0.088 | 0.394 | Denmark | 323 | 0.981 | 11.726 |
| Egypt | 33 | 0.100 | 0.494 | Switzerland | 351 | 1.066 | 12.792 |
| Taiwan | 60 | 0.182 | 0.676 | Finland | 406 | 1.233 | 14.025 |
| Greece | 63 | 0.191 | 0.867 | France | 414 | 1.258 | 15.283 |
| Luxembourg | 66 | 0.200 | 1.067 | Brazil | 535 | 1.625 | 16.908 |
| Colombia | 76 | 0.231 | 1.298 | Germany | 612 | 1.859 | 18.767 |
| Peru | 77 | 0.234 | 1.532 | South Africa | 748 | 2.272 | 21.039 |
| Philippines | 80 | 0.243 | 1.775 | Korea | 970 | 2.947 | 23.986 |
| Austria | 96 | 0.292 | 2.067 | India | 996 | 3.027 | 27.013 |
| Bermuda | 106 | 0.322 | 2.389 | Sweden | 1,050 | 3.19 | 30.203 |
| Indonesia | 109 | 0.331 | 2.720 | Hong Kong | 1,055 | 3.205 | 33.408 |
| Netherlands | 121 | 0.368 | 3.088 | Canada | 1,519 | 4.614 | 38.022 |
| Belgium | 130 | 0.395 | 3.483 | Australia | 1,728 | 5.249 | 43.271 |
| Spain | 140 | 0.425 | 3.908 | China | 2,647 | 8.041 | 51.312 |
| Argentina | 143 | 0.434 | 4.342 | UK | 2,696 | 8.19 | 59.502 |
| Thailand | 145 | 0.44 | 4.782 | Japan | 3,636 | 11.045 | 70.547 |
| Italy | 156 | 0.474 | 5.256 | U.S. | 9,696 | 29.453 | 100.000 |
| Total | | | | | 32,920 | 100.00 | |

Table 3: Exploratory data analysis: Summary and correlation**Panel A:** Descriptive statistics

| Variable | N | Mean | Std. Dev | 25% | Median | 75% | 95% |
|----------------------------------|--------|-----------|------------|---------|---------|-----------|------------|
| <i>Fim's financial outcomes</i> | | | | | | | |
| PD-1m (%) | 32,920 | 0.0225 | 0.2108 | 0.0002 | 0.0017 | 0.0092 | 0.0724 |
| PD-3m (%) | 32,920 | 0.0720 | 0.5626 | 0.0009 | 0.0070 | 0.0340 | 0.2422 |
| PD-6m (%) | 32,920 | 0.1566 | 0.9658 | 0.0031 | 0.0209 | 0.0882 | 0.5493 |
| PD-1y (%) | 32,920 | 0.3515 | 1.5330 | 0.0146 | 0.0730 | 0.2506 | 1.2970 |
| PD-2y (%) | 32,920 | 0.7870 | 2.2993 | 0.0766 | 0.2646 | 0.7140 | 2.8900 |
| CDS | 32,920 | 18.089 | 38.721 | 1.152 | 5.202 | 16.731 | 79.239 |
| DTD | 32,920 | 5.281 | 2.673 | 3.345 | 4.876 | 6.886 | 10.391 |
| Tobin's Q | 32,830 | 1.653 | 1.583 | 0.780 | 1.132 | 1.861 | 4.706 |
| ROA | 32,920 | 0.032 | 0.214 | 0.014 | 0.040 | 0.074 | 0.157 |
| <i>Climate change risk</i> | | | | | | | |
| CCE | 32,920 | 1.431 | 2.567 | 0.173 | 0.477 | 1.379 | 6.803 |
| OPE | 32,920 | 0.5457 | 1.6285 | 0.0000 | 0.0604 | 0.3056 | 3.0082 |
| RGE | 32,920 | 0.1021 | 0.3395 | 0.0000 | 0.0000 | 0.0000 | 0.5797 |
| PHE | 32,920 | 0.0205 | 0.1461 | 0.0000 | 0.0000 | 0.0000 | 0.1085 |
| CO ₂ | 29,985 | 3,803,880 | 13,800,000 | 59,300 | 272,000 | 1,397,515 | 17,900,000 |
| TCFD | 32,920 | 0.1676 | 0.3735 | 0.000 | 0.000 | 0.000 | 1.000 |
| <i>Firm control variables</i> | | | | | | | |
| SIZE | 32,920 | 4.719 | 2.542 | 3.275 | 4.793 | 6.288 | 8.720 |
| AGE | 32,920 | 2.987 | 1.057 | 2.303 | 2.944 | 3.526 | 4.394 |
| CF | 32,920 | 0.009 | 0.086 | (0.013) | 0.003 | 0.027 | 0.113 |
| LEV | 32,920 | 0.283 | 0.193 | 0.137 | 0.265 | 0.400 | 0.635 |
| CAPE | 32,920 | 0.049 | 0.045 | 0.018 | 0.037 | 0.065 | 0.141 |
| PPE | 32,920 | 0.418 | 0.407 | 0.120 | 0.314 | 0.633 | 1.119 |
| <i>Country control variables</i> | | | | | | | |
| GDP | 32,920 | 2.088 | 3.704 | 1.057 | 2.251 | 3.767 | 7.930 |
| IQ | 32,920 | 1.020 | 0.634 | 0.981 | 1.242 | 1.422 | 1.708 |

Panel B: Univariate analyses.

| Variable | High emitting sectors | | | | Low emitting sectors | | | | Mean1-Mean2 |
|----------------------------------|-----------------------|-----------|---------|------------|----------------------|---------|---------|-----------|--------------|
| | N | Mean1 | Median1 | Std. Dev1 | N | Mean2 | Median2 | Std. Dev2 | |
| <i>Fim's financial outcomes</i> | | | | | | | | | |
| PD-1m (%) | 14,811 | 0.0287 | 0.0027 | 0.2344 | 18,109 | 0.0174 | 0.0012 | 0.1892 | 0.0113*** |
| PD-3m (%) | 14,811 | 0.0908 | 0.0107 | 0.6056 | 18,109 | 0.0566 | 0.0048 | 0.5243 | 0.0342*** |
| PD-6m (%) | 14,811 | 0.1952 | 0.0308 | 1.0176 | 18,109 | 0.1251 | 0.0145 | 0.9202 | 0.0701*** |
| PD-1y (%) | 14,811 | 0.4315 | 0.1019 | 1.6121 | 18,109 | 0.2861 | 0.0525 | 1.4619 | 0.1454*** |
| PD-2y (%) | 14,811 | 0.9487 | 0.3490 | 2.4735 | 18,109 | 0.6548 | 0.2037 | 2.1373 | 0.2939*** |
| CDS | 14,811 | 29.7790 | 7.3048 | 144.9414 | 18,109 | 20.3550 | 3.8754 | 146.8958 | 9.424*** |
| DTD | 14,811 | 4.9843 | 4.5424 | 2.6949 | 18,109 | 5.7174 | 5.2510 | 2.9784 | -0.7332*** |
| Tobin's Q | 14,770 | 1.4204 | 0.9833 | 2.9820 | 18,060 | 2.3272 | 1.3414 | 5.0271 | -0.9069*** |
| ROA | 14,811 | 0.0325 | 0.0355 | 0.2702 | 18,109 | 0.0317 | 0.0438 | 0.1652 | 0.0008 |
| <i>Climate change risk</i> | | | | | | | | | |
| CCE | 14,811 | 2.8831 | 1.1679 | 4.5317 | 18,109 | 0.6580 | 0.2791 | 1.4417 | 2.2250*** |
| OPE | 14,811 | 0.9825 | 0.1887 | 2.2088 | 18,109 | 0.2070 | 0.0000 | 0.8144 | 0.7755*** |
| RGE | 14,811 | 0.1933 | 0.0000 | 0.4740 | 18,109 | 0.0313 | 0.0000 | 0.1380 | 0.162*** |
| PHE | 14,811 | 0.0383 | 0.0000 | 0.2131 | 18,109 | 0.0067 | 0.0000 | 0.0471 | 0.0316*** |
| CO ₂ | 13,491 | 6,932,728 | 639,000 | 18,900,000 | 16,494 | 714,727 | 146,496 | 2,008,740 | 6,218,001*** |
| TCFD | 14,811 | 0.2003 | 0.0000 | 0.4003 | 18,109 | 0.1409 | 0.0000 | 0.3479 | 0.0595*** |
| <i>Firm control variables</i> | | | | | | | | | |
| SIZE | 14,811 | 8.4368 | 8.4959 | 1.6134 | 18,109 | 8.1517 | 8.1626 | 1.7250 | 0.2851*** |
| AGE | 14,747 | 3.3513 | 3.2958 | 1.1196 | 18,032 | 3.2413 | 3.1781 | 1.1252 | 0.11*** |
| CF | 14,811 | 0.0056 | 0.0024 | 0.0648 | 18,109 | 0.0116 | 0.0043 | 0.0998 | -0.006*** |
| LEV | 14,811 | 0.3540 | 0.2817 | 5.9676 | 18,109 | 0.3822 | 0.2532 | 12.2294 | -0.0282 |
| CAPE | 14,811 | 0.0891 | 0.0400 | 4.0342 | 18,109 | 0.0486 | 0.0339 | 0.1173 | 0.0405 |
| PPE | 14,811 | 0.5057 | 0.4243 | 0.4605 | 18,109 | 0.3472 | 0.2454 | 0.3402 | 0.1586*** |
| <i>Country control variables</i> | | | | | | | | | |
| GDP | 14,811 | 2.0276 | 2.2419 | 3.6244 | 18,109 | 2.1374 | 2.2807 | 3.7678 | -0.1098*** |
| IQ | 14,811 | 1.0507 | 1.2486 | 0.6319 | 18,109 | 0.9942 | 1.2361 | 0.6340 | 0.0565*** |

Note: This table presents the differences in financial outcome measures, firm-level climate change exposure, and control variables between two subsamples: firms operating in high- and low-emitting industries. Variable definitions are provided in Appendix A. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel C: Correlation analysis

| # | Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|----|-----------------|-----------|----------|-----------|----------|----------|----------|----------|----------|----------|---------|---------|
| 1 | PD-1m | 1.00 | | | | | | | | | | |
| 2 | PD-3m | 0.89*** | 1.00 | | | | | | | | | |
| 3 | PD-6m | 0.88*** | 0.88*** | 1.00 | | | | | | | | |
| 4 | PD-1y | 0.87*** | 0.78*** | 0.89*** | 1.00 | | | | | | | |
| 5 | PD-2y | 0.93*** | 0.85*** | 0.86*** | 0.91*** | 1.00 | | | | | | |
| 6 | DTD | -0.29*** | -0.30*** | -0.32*** | -0.36*** | -0.40*** | 1.00 | | | | | |
| 7 | CDS | 0.96*** | 0.97*** | 0.99*** | 0.99*** | 0.97*** | -0.35*** | 1.00 | | | | |
| 8 | Tobin's Q | -0.08*** | -0.09*** | -0.10*** | -0.11*** | -0.12*** | 0.35*** | -0.11*** | 1.00 | | | |
| 9 | ROA | -0.19*** | -0.19*** | -0.20*** | -0.22*** | -0.22*** | 0.43*** | -0.22*** | 0.15*** | 1.00 | | |
| 10 | CCE | 0.018*** | 0.016*** | 0.015*** | 0.017*** | 0.019*** | -0.04*** | 0.01 | -0.10*** | -0.06*** | 1.00 | |
| 11 | OPE | 0.0173*** | 0.017*** | 0.0172*** | 0.018*** | 0.021*** | -0.03* | 0.01 | -0.07*** | -0.06*** | 0.72*** | 1.00 |
| 12 | RGE | 0.005*** | 0.006*** | 0.011** | 0.026** | 0.056*** | -0.04** | 0.00 | -0.07*** | -0.03** | 0.56*** | 0.39*** |
| 13 | PHE | 0.048** | 0.048*** | 0.05** | 0.058** | 0.081** | 0.00 | 0.00 | -0.02 | 0.00 | 0.21*** | 0.15*** |
| 14 | CO ₂ | 0.08*** | 0.08*** | 0.08*** | 0.08*** | 0.09*** | -0.04*** | 0.08*** | -0.09*** | -0.04** | 0.26*** | 0.21*** |
| 15 | TCFD | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | -0.01 | 0.02 | -0.01 | 0.00 | 0.02 | 0.01 |
| 16 | SIZE | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.08*** | 0.00 | -0.22*** | -0.02 | 0.09*** | 0.08*** |
| 17 | AGE | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | -0.01 | -0.02 | -0.02 | -0.01 | 0.00 | -0.01 |
| 18 | CF | -0.03** | -0.03** | -0.04** | -0.04** | -0.04** | -0.02 | -0.04*** | 0.04*** | 0.02 | -0.02 | -0.01 |
| 19 | LEV | 0.09*** | 0.08*** | 0.09*** | 0.09*** | 0.11*** | -0.20*** | 0.09*** | -0.06*** | -0.16*** | 0.06*** | 0.06*** |
| 20 | CAPE | -0.03** | -0.04** | -0.04** | -0.04** | -0.03** | 0.04*** | -0.04** | 0.02 | 0.08*** | 0.07*** | 0.05*** |
| 21 | PPE | 0.03* | 0.03* | 0.03* | 0.03* | 0.03** | -0.03* | 0.03* | -0.13*** | -0.04** | -0.04** | -0.04** |
| 22 | GDP | -0.02 | -0.03* | -0.02* | -0.02 | 0.00 | 0.18*** | -0.02 | 0.05*** | 0.12*** | 0.05*** | 0.03** |
| 23 | IQ | -0.19*** | -0.18*** | -0.18*** | -0.18*** | -0.20*** | 0.10*** | -0.16*** | -0.05*** | -0.04*** | -0.02 | -0.01 |

| # | Variables | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|----|-----------------|---------|---------|----------|---------|----------|----------|----------|---------|----------|--------|----------|------|
| 12 | RGE | 1.00 | | | | | | | | | | | |
| 13 | PHE | 0.07*** | 1.00 | | | | | | | | | | |
| 14 | CO ₂ | 0.20*** | 0.00 | 1.00 | | | | | | | | | |
| 15 | TCFD | 0.02 | 0.00 | 0.02 | 1.00 | | | | | | | | |
| 16 | SIZE | 0.09*** | 0.01 | 0.28*** | 0.04*** | 1.00 | | | | | | | |
| 17 | AGE | 0.03** | 0.00 | -0.01 | 0.00 | -0.03* | 1.00 | | | | | | |
| 18 | CF | 0.01 | 0.00 | -0.02 | 0.01 | -0.04*** | -0.02 | 1.00 | | | | | |
| 19 | LEV | 0.03* | -0.01 | 0.06*** | 0.00 | 0.07*** | -0.01 | 0.05*** | 1.00 | | | | |
| 20 | CAPE | 0.04*** | 0.00 | 0.08*** | 0.02 | 0.00 | 0.03** | -0.01 | 0.09*** | 1.00 | | | |
| 21 | PPE | 0.01 | 0.05*** | 0.09*** | -0.02 | 0.06*** | 0.03** | -0.06*** | 0.06*** | 0.33*** | 1.00 | | |
| 22 | GDP | 0.06*** | 0.01 | 0.03* | 0.06*** | 0.03* | -0.03* | -0.12*** | -0.03** | 0.07*** | 0.04** | 1.00 | |
| 23 | IQ | 0.03* | 0.02 | -0.10*** | -0.02 | 0.01 | -0.04*** | -0.03* | -0.04** | -0.10*** | 0.01 | -0.08*** | 1.00 |

Table 4. The effect of CCE on firms' financial outcomes (Benchmark model)*Panel A: The effect of firm-level climate risk on default risk*

| Variable | Dependent variable = firms' default risk | | | | | | | |
|--------------------|--|-----------------------|-----------------------|-----------------------|---------------------|-----------------------|-----------------------|-----------------------|
| | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] |
| | PD-1m | PD-1m | PD-1m | PD-1m | CDS | CDS | CDS | CDS |
| Constant | 0.218*** [14.685] | 0.663*** [6.724] | 0.280*** [2.606] | 0.646*** [6.404] | 0.260*** [5.246] | 0.514*** [6.237] | 0.314*** [3.788] | 0.507*** [7.410] |
| CCE | 0.389*** [2.699] | 0.323** [2.432] | | 0.117*** [3.466] | 0.226*** [2.708] | 0.250*** [4.129] | | 0.763*** [3.601] |
| TCFD | | | -0.996*** [-4.882] | -0.068** [-2.100] | | | -0.742*** [-4.727] | -0.438** [-2.206] |
| TCFD×CCE | | | | -2.894*** [-2.748] | | | | -1.758*** [-2.662] |
| SIZE | | -0.022** [-2.308] | -0.051*** [-3.738] | -0.018* [-1.846] | | -0.078 [-1.321] | 0.042*** [3.915] | -0.056 [-0.830] |
| AGE | | -0.508*** [-4.100] | -0.495*** [-3.830] | -0.505*** [-3.974] | | -0.498*** [-3.684] | -0.514*** [-5.110] | -0.504*** [-5.843] |
| CF | | -0.346*** [-3.431] | 0.0947 [0.707] | -0.351*** [-3.413] | | -0.360*** [-3.546] | -0.029 [-0.328] | -0.376** [-2.560] |
| LEV | | 0.339*** [5.013] | 0.136 [0.011] | 0.297*** [4.246] | | 0.343*** [4.903] | -0.078 [-0.091] | 0.325*** [7.260] |
| CAPE | | -1.813*** [-6.561] | -0.0186 [-0.400] | -1.759*** [-6.247] | | -1.401*** [-5.454] | -0.0153 [-0.488] | -1.364*** [-7.829] |
| PPE | | -0.300*** [-8.135] | -0.132*** [-3.629] | -0.314*** [-8.292] | | -0.215*** [-3.128] | -0.0607** [-2.275] | -0.224*** [-8.934] |
| GDP | | -0.143*** [-3.758] | -0.176 [-0.346] | -0.146*** [-3.625] | | -0.122*** [-4.984] | -0.079 [-0.750] | -0.127*** [-5.299] |
| IQ | | -0.207*** [-8.313] | -0.127*** [-4.019] | -0.204*** [-8.065] | | -0.153*** [-7.949] | -0.077*** [-3.196] | -0.152*** [-8.893] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 32,920 | 32,920 | 32,920 | 32,920 | 32,920 | 32,920 | 32,920 | 32,920 |
| Wald χ^2 | 7.283*** | 193*** | 172*** | 191*** | 7.332*** | 151*** | 167*** | 294*** |
| (Prob > χ^2) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel B: The effect of firm-level climate risk on firm value

| Variable | Dependent variable = Firm value | | | | | | | |
|-------------------------|---------------------------------|------------------------|------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|
| | [Model 9] | [Model 10] | [Model 11] | [Model 12] | [Model 13] | [Model 14] | [Model 15] | [Model 16] |
| | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | ROA | ROA | ROA | ROA |
| Constant | 1.187*** [8.671] | 1.764*** [8.631] | 6.414*** [9.183] | 2.854*** [5.958] | 2.031*** [7.563] | 10.90*** [4.811] | -0.244*** [-10.176] | 12.46*** [3.988] |
| CCE | -0.170*** [-4.980] | -0.093** [-2.250] | | -0.761*** [-3.689] | -0.385*** [-3.419] | -0.308*** [-2.694] | | -0.604*** [-3.733] |
| TCFD | | | 2.313*** [4.725] | 5.052*** [2.869] | | | -2.001*** [-5.758] | 0.312** [2.362] |
| TCFD×CCE | | | | 1.561** [2.553] | | | | 1.123** [2.119] |
| SIZE | | -0.767*** [-12.450] | -0.452*** [-11.215] | -0.164*** [-7.157] | | 0.929*** [5.216] | 0.033*** [11.189] | 1.109*** [12.157] |
| AGE | | -0.172** [-2.291] | -0.608** [-2.473] | 0.176 [0.751] | | 0.355** [2.149] | 0.051* [1.690] | 0.409*** [3.551] |
| CF | | 0.503* [1.912] | 0.719*** [5.779] | 0.697* [1.575] | | 3.759** [2.421] | 0.245*** [29.414] | 4.162*** [4.633] |
| LEV | | -0.313** [-2.457] | -0.175** [-2.271] | -0.274*** [-3.503] | | -1.145** [-2.152] | -0.108*** [-2.807] | -0.829** [-2.250] |
| CAPE | | 0.918*** [11.982] | 0.853* [1.687] | 1.679*** [8.867] | | 0.922 [0.925] | 0.141*** [9.170] | 0.564 [0.438] |
| PPE | | -0.561*** [-4.886] | -0.242*** [-5.043] | -0.206*** [-6.711] | | 0.294** [2.231] | -0.001 [-0.233] | 0.260** [2.200] |
| GDP | | 0.620*** [7.813] | 0.531*** [5.326] | -0.039 [-0.675] | | 0.227** [2.422] | 0.195*** [4.443] | 0.109*** [3.736] |
| IQ | | 0.177 [1.122] | 0.920*** [10.042] | 0.633*** [5.034] | | 0.144*** [3.998] | 0.0127* [1.908] | 0.111*** [3.479] |
| Year FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Sector FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Country FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 32,830 | 32,830 | 32,830 | 32,830 | 32,920 | 32,920 | 32,920 | 32,920 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel C: High vs low climate change exposure-intensive industry

| Variable | <i>DV= Firms' default risk</i> | | <i>DV= Firm value</i> | |
|-------------------------|--------------------------------|-----------------------|------------------------|------------------------|
| | [Model 1] | [Model 2] | [Model 3] | [Model 4] |
| | PD-1m | CDS | Tobin's Q | ROA |
| Constant | 0.670*** [3.680] | 3.269*** [7.054] | 7.572*** [5.867] | 7.308*** [4.065] |
| CCE | 0.017** [2.091] | 0.074*** [11.318] | -0.099*** [-7.535] | -0.150*** [-35.293] |
| High Emission | 0.083*** [2.608] | 3.184*** [3.536] | -0.119*** [-5.862] | -0.866*** [-25.763] |
| CCE×High Emission | 0.435** [1.976] | 0.397*** [5.213] | -0.023*** [-16.384] | -0.105*** [-4.468] |
| SIZE | -0.027*** [-3.069] | -1.204*** [-7.501] | -0.250*** [-11.665] | 0.214*** [6.184] |
| AGE | -0.102*** [-7.089] | -0.208*** [-4.040] | -0.206*** [-24.064] | 0.436*** [3.143] |
| CF | -0.216* [-1.677] | -1.502*** [-3.252] | 3.128*** [5.954] | 2.164*** [19.323] |
| LEV | 0.388*** [4.082] | 2.168*** [8.794] | -0.369*** [-3.465] | -1.368*** [-4.400] |
| CAPE | -1.619*** [-4.591] | -1.339*** [-8.432] | 3.473*** [8.998] | 4.624*** [4.233] |
| PPE | 0.193* [1.701] | 1.797*** [10.726] | -0.406*** [-5.417] | 0.448*** [3.089] |
| GDP | -0.708* [-1.782] | -0.741*** [-9.287] | 0.325*** [3.494] | 0.346*** [26.937] |
| IQ | -0.186*** [-7.799] | -1.490*** [-3.839] | 0.224*** [7.312] | 0.154*** [21.312] |
| <i>Year FE</i> | Yes | Yes | Yes | Yes |
| <i>Sector FE</i> | Yes | Yes | Yes | Yes |
| <i>Country FE</i> | Yes | Yes | Yes | Yes |
| Observation | 32,920 | 32,920 | 32,830 | 32,920 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 |

Table 5: Endogeneity issues

Panel A: First-stage regression using caliper matching

| Dependent variable | |
|--|-----------------------|
| Treatment group = High climate change exposure | |
| Constant | -2.425*** [-3.902] |
| SIZE | 0.118*** [4.054] |
| AGE | 0.002 [0.486] |
| CF | -0.321*** [-3.172] |
| LEV | 0.318 [0.970] |
| CAPE | -0.139 [-0.706] |
| PPE | 0.187*** [6.826] |
| GDP | -0.257 [-0.733] |
| IQ | -0.121*** [-5.682] |
| <i>Year FE</i> | Yes |
| <i>Sector FE</i> | Yes |
| <i>Country FE</i> | Yes |
| Observation | 36,956 |
| <i>R-squared</i> | 0.0112 |
| (Prob > χ^2) | 0.000 |

Panel B: Balancing test

| Variable | Mean | | % bias | t-test | |
|----------|---------|---------|---------|---------|-------|
| | Treated | Control | | t | p>t |
| SIZE | 8.0166 | 8.0167 | 0.000 | 0.000 | 0.998 |
| AGE | 3.1087 | 3.0777 | 2.700 | 2.630 | 0.009 |
| CF | 0.006 | 0.006 | (0.400) | (0.400) | 0.693 |
| LEV | 0.371 | 0.332 | 0.300 | 0.840 | 0.401 |
| CAPE | 0.058 | 0.051 | 0.000 | 1.660 | 0.097 |
| PPE | 0.463 | 0.466 | (0.600) | (0.590) | 0.554 |
| GDP | 1.977 | 1.932 | 1.500 | 1.460 | 0.145 |
| IQ | 1.120 | 1.122 | (0.400) | (0.400) | 0.688 |

Panel C: Second stage regression results using PSM samples

| Variable | Dependent variable = Firm's default risk | | | | | | | |
|-------------------------|--|------------------------|------------------------|-----------------------|----------------------|-----------------------|------------------------|------------------------|
| | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] |
| | PD-1m | PD-1m | PD-1m | PD-1m | CDS | CDS | CDS | CDS |
| Constant | 0.161*** [19.682] | 0.600*** [5.555] | 0.027** [3.133] | 0.714*** [6.417] | 0.210*** [31.459] | 0.539*** [6.083] | 0.111*** [3.979] | 0.617*** [6.782] |
| CCE | 0.0412*** [5.833] | 0.0263*** [5.072] | | 0.102*** [7.655] | 0.0353*** [6.144] | 0.0234*** [5.499] | | 0.0858*** [7.893] |
| TCFD | | | -11.15*** [-7.982] | -0.0301** [-2.005] | | | -7.185*** [-8.905] | -0.0410*** [-3.339] |
| TCFD×CCE | | | | -2.536*** [-6.188] | | | | -2.094*** [-6.247] |
| SIZE | | -0.125*** [-2.675] | -0.285*** [-2.997] | -0.170*** [-3.520] | | -0.0960** [-2.505] | -0.232*** [-4.399] | -0.125*** [-3.171] |
| AGE | | -0.824*** [-3.139] | -0.134*** [-3.846] | -0.966*** [-3.507] | | -0.814*** [-3.774] | -0.819*** [-4.187] | -0.953*** [-4.229] |
| CF | | -0.205* [-1.749] | -2.273*** [-26.198] | -0.206* [-1.739] | | -0.272*** [-2.831] | -0.269*** [-4.254] | -0.277*** [-2.860] |
| LEV | | 0.285*** [8.537] | 0.0228*** [4.760] | 0.294*** [8.672] | | 0.303*** [11.074] | 0.312*** [14.663] | 0.307*** [11.084] |
| CAPE | | -1.082*** [-7.701] | -0.215*** [-4.269] | -1.070*** [-7.528] | | -1.012*** [-8.781] | -0.540*** [-7.571] | -0.989*** [-8.522] |
| PPE | | -0.115*** [-6.498] | -0.644*** [-2.969] | -0.121*** [-6.721] | | -0.109*** [-7.533] | -0.530*** [-3.959] | -0.114*** [-7.767] |
| GDP | | -0.118*** [-6.022] | -0.116*** [-3.071] | -0.124*** [-6.150] | | -0.969*** [-6.032] | -0.342* [-1.655] | -0.101*** [-6.161] |
| IQ | | -0.200*** [-15.603] | -0.105*** [-4.251] | -0.205*** [-5.694] | | -0.168*** [-6.009] | -0.0947*** [-6.503] | -0.170*** [-5.935] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 19,287 | 19,287 | 19,287 | 19,287 | 19,287 | 19,287 | 19,287 | 19,287 |
| <i>R-squared</i> | 0.026 | 0.285 | 0.289 | 0.316 | 0.029 | 0.341 | 0.359 | 0.377 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel D: Second stage regression results using PSM samples

| Variable | Dependent variable = Firm value | | | | | | | |
|-------------------------|---------------------------------|------------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | [Model 9] | [Model 10] | [Model 11] | [Model 12] | Model 13] | [Model 14] | [Model 15] | [Model 16] |
| | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | ROA | ROA | ROA | ROA |
| Constant | 1.193*** [7.271] | 2.464*** [7.578] | 8.861*** [5.143] | 4.924*** [8.077] | 2.377** [2.522] | 8.838*** [4.760] | 0.0257*** [8.262] | 3.517*** [8.793] |
| CCE | -0.945*** [-21.991] | -0.103*** [-24.341] | | -0.524** [-2.432] | -0.365*** [-4.135] | -0.393*** [-4.439] | | -0.962*** [-3.837] |
| TCFD | | | 3.081*** [10.243] | 2.286*** [7.407] | | | 2.258*** [18.536] | 0.0438 [0.156] |
| TCFD×CCE | | | | 1.123** [2.654] | | | | 2.611*** [3.148] |
| SIZE | | -0.568*** [-14.809] | -0.301*** [-10.842] | -0.166*** [-5.681] | | 0.237*** [2.958] | 0.212*** [9.084] | -0.145 [-1.546] |
| AGE | | 0.129 [0.632] | -0.366** [-2.559] | -0.073 [-0.501] | | -0.006 [-1.329] | 0.702* [1.844] | -0.658 [-1.243] |
| CF | | 0.196* [1.908] | -0.482*** [-4.060] | -0.862*** [-5.957] | | 5.123** [2.545] | 0.128*** [10.185] | 5.464** [2.520] |
| LEV | | -0.232*** [-8.042] | -0.148*** [-2.826] | -0.891 [-1.413] | | -2.416*** [-4.223] | -0.652*** [-3.149] | -2.616*** [-4.217] |
| CAPE | | 0.798*** [6.611] | 1.133*** [6.695] | 1.193*** [5.285] | | 3.550 [1.469] | 0.0933*** [6.592] | 4.039 [1.537] |
| PPE | | -0.196*** [-14.286] | -0.150*** [-4.288] | -0.236*** [-6.513] | | 1.266*** [4.171] | 0.161*** [5.406] | 1.497*** [4.463] |
| GDP | | 0.124*** [7.993] | 0.527*** [8.412] | 0.368*** [5.623] | | 0.448** [2.344] | 0.0153*** [4.321] | 0.653* [1.743] |
| IQ | | 0.567 [0.566] | 0.825*** [3.801] | 0.752*** [11.739] | | 0.984*** [3.458] | 0.347*** [4.454] | 0.254*** [3.070] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 20,810 | 20,810 | 20,810 | 20,810 | 19,287 | 19,287 | 19,287 | 19,287 |
| <i>R-squared</i> | 0.039 | 0.081 | 0.088 | 0.085 | 0.011 | 0.051 | 0.547 | 0.047 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 6: Robustness tests - alternative scaling of climate risk

| Variable | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] | [Model 9] | [Model 10] | [Model 11] | [Model 12] |
|-------------------------|----------------------|-----------------------|-----------------------|---------------------|-----------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | PD-1m | PD-1m | PD-1m | CDS | CDS | CDS | Tobin's Q | Tobin's Q | Tobin's Q | ROA | ROA | ROA |
| Constant | 0.0563*** [3.906] | 1.321*** [5.624] | 0.0411*** [3.113] | 0.0247** [2.630] | 0.978*** [6.140] | 0.147** [2.616] | 3.056*** [7.776] | 4.298*** [8.747] | 8.302*** [11.793] | 5.564*** [12.535] | 4.467*** [5.760] | 5.852** [2.087] |
| CO ₂ | 0.228*** [4.447] | 0.354*** [4.535] | 0.526*** [6.126] | 0.204*** [6.139] | 0.348*** [6.735] | 0.485*** [8.710] | -0.639*** [-3.758] | -0.734*** [-5.758] | -0.793*** [-4.978] | -0.306*** [-8.225] | -0.210*** [-7.363] | -0.260*** [-3.124] |
| TCFD | | | -0.110*** [-3.381] | | | -0.0813*** [-4.064] | | | 1.870*** [3.468] | | | 2.524*** [7.960] |
| TCFD×CO ₂ | | | -0.742*** [-4.759] | | | -0.632*** [-6.173] | | | 0.800** [2.488] | | | 6.192*** [2.808] |
| SIZE | | -0.645*** [-5.100] | -0.083*** [-3.474] | | -0.499*** [-5.845] | -0.319*** [-3.280] | | -0.419* [-1.817] | -0.241*** [-6.856] | | 0.582** [2.208] | 0.633*** [3.443] |
| AGE | | -0.113** [-2.249] | -0.101* [-1.899] | | -0.995*** [-2.937] | -0.883** [-2.533] | | -0.123** [-2.517] | -0.372** [-2.498] | | 0.471*** [4.436] | -0.606 [-1.284] |
| CF | | -0.284 [-1.186] | -0.245 [-0.997] | | -0.311** [-2.195] | -0.299** [-2.048] | | 0.542*** [4.386] | 0.601*** [4.766] | | 3.673*** [4.159] | 3.959*** [4.159] |
| LEV | | 0.380*** [5.672] | 0.330*** [4.750] | | 0.387*** [9.045] | 0.365*** [8.339] | | -0.115** [-2.104] | -0.084 [-1.482] | | -1.279*** [-5.655] | -0.899** [-2.368] |
| CAPE | | -1.840*** [-6.677] | -1.802*** [-6.415] | | -1.450*** [-8.513] | -1.422*** [-8.237] | | 1.039*** [5.578] | 1.281*** [6.711] | | 2.547*** [19.317] | -0.028 [-0.021] |
| PPE | | -0.220*** [-5.534] | -0.221*** [-5.425] | | -0.142*** [-5.499] | -0.141*** [-5.380] | | -0.204*** [-6.472] | -0.144*** [-4.396] | | 0.269*** [7.097] | -0.075 [-0.326] |
| GDP | | -0.122*** [-3.238] | -0.358** [-2.686] | | -0.101*** [-4.496] | 0.369 [1.126] | | 0.132 [0.693] | 0.530*** [7.481] | | 0.356*** [24.438] | 0.349*** [9.915] |
| IQ | | -0.191*** [-7.669] | -0.0611* [-1.686] | | -0.138*** [-8.292] | -0.319 [-1.369] | | 0.456*** [6.649] | 0.597*** [8.245] | | 0.118*** [13.316] | 1.982*** [7.432] |
| Year FE | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Sector FE | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Country FE | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Observation | 29,985 | 29,985 | 20,775 | 29,985 | 29,985 | 20,775 | 29,985 | 29,985 | 20,775 | 29,985 | 20,775 | 20,775 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 7: Robustness tests - the alternative dependent measures

Panel A: The joint effect of TCFD and Climate change exposure on firms' financial outcomes

| Variable | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] | [Model 9] |
|--------------------|------------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|------------------------|
| | DTD | DTD | DTD | PD-3m | PD-3m | PD-3m | PD-6m | PD-6m | PD-6m |
| Constant | 1.305*** [2.661] | 2.528*** [7.536] | 7.558*** [12.359] | 2.564*** [4.672] | 1.294** [2.660] | 2.370*** [4.197] | 4.779*** [4.710] | 1.532*** [3.073] | 4.419*** [4.458] |
| CCE | -0.142*** [-7.659] | | -0.163*** [-8.530] | 0.951*** [2.810] | | 0.354*** [4.092] | 0.185*** [3.079] | | 0.663*** [4.561] |
| TCFD | | 0.108*** [3.292] | 4.027*** [7.809] | | -2.908*** [-5.254] | -0.211** [-2.564] | | -4.871*** [-4.830] | -0.377*** [-2.745] |
| TCFD×CCE | | | 1.065** [2.520] | | | -8.814*** [-3.274] | | | -1.632*** [-3.601] |
| SIZE | 0.134*** [6.133] | 0.618*** [4.044] | 0.170*** [6.107] | -0.729*** [-3.025] | -0.136*** [-3.651] | -0.618** [-2.484] | -0.123*** [-2.752] | 0.230*** [3.356] | -0.104** [-2.377] |
| AGE | 0.324*** [2.670] | 0.300*** [2.669] | 0.165 [1.302] | -0.342*** [-2.641] | -0.328** [-2.145] | -0.362*** [-2.665] | -0.716*** [-3.027] | -0.689** [-2.421] | -0.745*** [-3.144] |
| CF | 0.959*** [4.080] | 0.114 [0.897] | 0.734*** [3.038] | -1.091* [-1.778] | 0.0282 [0.081] | -1.105* [-1.757] | -2.191** [-2.195] | -0.609 [-1.049] | -2.349** [-2.284] |
| LEV | -2.590*** [-27.723] | 0.108*** [7.999] | 2.754*** [-28.118] | 1.199*** [6.973] | 0.268 [0.080] | 1.076*** [6.048] | 2.521*** [8.421] | 0.024 [0.043] | 2.351*** [7.774] |
| CAPE | 4.821*** [14.513] | 0.344*** [6.935] | 5.394*** [15.895] | -5.140*** [-7.288] | -0.486 [-0.396] | -4.970*** [-6.920] | -9.863*** [-8.265] | -0.887 [-0.430] | -9.483*** [-7.899] |
| PPE | 0.345*** [6.260] | 0.286*** [7.232] | 0.509*** [8.912] | -0.828*** [-8.825] | -0.353*** [-3.619] | -0.868*** [-8.984] | -1.509*** [-8.974] | -0.554*** [-3.209] | -1.584*** [-9.492] |
| GDP | 0.134*** [36.523] | 0.132*** [44.513] | 0.128*** [16.83] | -0.391*** [-4.031] | -0.075 [-0.550] | -0.040*** [-3.906] | -0.875*** [-5.530] | -0.388 [-1.616] | -0.850*** [-5.056] |
| IQ | 1.094*** [19.181] | 0.870*** [20.492] | 0.508*** [8.437] | -0.627*** [-9.893] | -0.388*** [-4.534] | -0.619*** [-9.544] | -1.259*** [-10.916] | -0.851*** [-5.491] | -1.253*** [-11.135] |
| <i>Year FE</i> | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| <i>Sector FE</i> | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| <i>Country FE</i> | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observation | 32,920 | 32,874 | 32,874 | 32,920 | 32,920 | 32,874 | 32,920 | 32,920 | 32,874 |
| (Prob > χ^2) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel B: The joint effect of TCFD and Climate change exposure on firms' financial outcomes

| Variable | [Model 10] | [Model 11] | [Model 12] | [Model 13] | [Model 14] | [Model 15] |
|-------------------------|------------------------|-----------------------|------------------------|------------------------|-----------------------|------------------------|
| | PD-1Y | PD-1Y | PD-1Y | PD-2Y | PD-2Y | PD-2Y |
| Constant | 8.194*** [4.354] | 0.133*** [4.054] | 7.529*** [3.990] | 1.252*** [3.951] | 0.354** [2.914] | 1.186*** [3.690] |
| CCE | 0.316*** [3.161] | | 0.887*** [3.867] | 0.491*** [3.361] | | 0.114*** [3.527] |
| TCFD | | -6.592*** [-3.859] | -0.416** [-1.992] | | -6.652** [-2.522] | -0.379** [-1.327] |
| TCFD×CCE | | | -1.970*** [-2.778] | | | -2.243** [-2.268] |
| SIZE | -0.155* [-1.862] | -0.335*** [2.838] | -0.123** [-2.469] | -0.782 [-0.556] | 0.491*** [2.632] | -0.471 [-0.330] |
| AGE | -0.148*** [-3.390] | -0.142*** [-2.822] | -0.156*** [-3.502] | -0.028*** [-3.765] | -0.027*** [-3.299] | -0.296*** [-3.856] |
| CF | -4.265*** [-2.951] | -2.467*** [-2.851] | -4.415*** [-2.980] | -0.821*** [-4.204] | -0.544*** [-4.580] | -0.848*** [-4.244] |
| LEV | 5.050*** [10.323] | -0.392 [-0.046] | 4.876*** [9.713] | 0.980*** [13.581] | -0.284 [-0.234] | 0.983*** [13.179] |
| CAPE | -1.843*** [-9.931] | -0.164 [-0.519] | -1.773*** [-9.449] | -3.229*** [-12.223] | -0.299 [-0.673] | -3.150*** [-11.757] |
| PPE | -2.314*** [-8.102] | -0.652** [-2.346] | -2.434*** [-8.367] | -0.296*** [-6.944] | 0.559 [1.383] | -0.306*** [-6.968] |
| GDP | -0.187*** [-8.162] | -0.124*** [-3.178] | -0.196*** [-8.078] | -0.302*** [-9.798] | -0.248*** [-4.246] | -0.328*** [-10.053] |
| IQ | -2.527*** [-11.916] | -1.896*** [-7.215] | -2.522*** [-11.978] | -0.505*** [-14.028] | -0.400*** [-9.729] | -0.504*** [-13.958] |
| <i>Year FE</i> | Yes | Yes | Yes | Yes | Yes | Yes |
| <i>Sector FE</i> | Yes | Yes | Yes | Yes | Yes | Yes |
| <i>Country FE</i> | Yes | Yes | Yes | Yes | Yes | Yes |
| Observation | 32,920 | 31,751 | 31,751 | 32,920 | 31,751 | 31,751 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 8: Robustness tests -Alternative dependent and independent variable

Panel A: the joint effect of TCFD and carbon emission on firms' default risk (PD-3m and PD-6m)

| Variable | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] |
|-------------------------|---------------------|-----------------------|-----------------------|-----------------------|---------------------|------------------------|-----------------------|-----------------------|
| | PD-3m | PD-3m | PD-3m | PD-3m | PD-6m | PD-6m | PD-6m | PD-6m |
| Constant | 0.129** [2.776] | 3.863*** [6.409] | 1.294*** [3.660] | 0.274*** [4.293] | 0.166*** [4.559] | 7.571*** [6.825] | 1.532*** [3.073] | 0.728*** [4.450] |
| CO ₂ | 0.693*** [5.023] | 0.105*** [5.235] | | 0.157*** [7.121] | 0.144*** [5.794] | 0.225*** [6.239] | | 0.321*** [8.467] |
| TCFD | | | -2.908*** [-5.254] | -0.330*** [-3.960] | | | -4.871*** [-4.830] | -0.617*** [-4.432] |
| TCFD×C02 | | | | -2.257*** [-5.656] | | | | -4.544*** [-6.560] |
| SIZE | | -0.187*** [-5.755] | -0.136*** [-3.651] | -0.0157 [-0.352] | | -0.368*** [-6.181] | -0.230*** [-3.356] | -0.0213 [-0.275] |
| AGE | | -0.340*** [-2.628] | -0.328** [-2.145] | -0.302** [-2.216] | | -0.715*** [-3.031] | -0.689** [-2.421] | -0.621*** [-2.634] |
| CF | | -0.958 [-1.560] | 0.282 [0.081] | -0.846 [-1.344] | | -1.939* [-1.942] | -0.609 [-1.049] | -1.874* [-1.821] |
| LEV | | 1.234*** [7.176] | 0.268 [0.080] | 1.087*** [6.114] | | 2.614*** [8.731] | 0.024 [0.043] | 2.398*** [7.958] |
| CAPE | | -5.379*** [-7.608] | -0.486 [-0.396] | -5.262*** [-7.315] | | -1.038*** [-8.679] | -0.887 [-0.430] | -1.008*** [-8.401] |
| PPE | | -0.612*** [-6.007] | -0.353*** [-3.619] | -0.614*** [-5.879] | | -1.062*** [-5.856] | -0.554*** [-3.209] | -1.065*** [-5.944] |
| GDP | | -0.361*** [-3.725] | -0.075 [-0.550] | 0.012 [0.900] | | -0.809*** [-5.112] | -0.388 [-1.616] | 0.022 [0.976] |
| IQ | | -0.584*** [-9.122] | -0.388*** [-4.534] | -0.187** [-2.020] | | -1.167*** [-10.028] | -0.851*** [-5.491] | -0.398** [-2.499] |
| Year FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Sector FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Country FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 29,985 | 29,985 | 29,985 | 20,207 | 29,985 | 29,985 | 20,207 | 20,207 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel B: the joint effect of TCFD and carbon emission on firms' default risk (PD-1Y and PD-2Y)

| Variable | [Model 9] | [Model 10] | [Model 11] | [Model 12] | [Model 13] | [Model 14] | [Model 15] | [Model 16] |
|-------------------------|---------------------|------------------------|-----------------------|------------------------|---------------------|------------------------|-----------------------|------------------------|
| | PD-1Y | PD-1Y | PD-1Y | PD-1Y | PD-2Y | PD-2Y | PD-2Y | PD-2Y |
| Constant | 0.0441** [2.085] | 1.417*** [6.943] | 0.133** [2.054] | 0.348*** [3.117] | 0.871** [2.007] | 2.354*** [6.928] | 3.540*** [2.914] | 0.374** [2.076] |
| CO ₂ | 0.304*** [7.007] | 0.485*** [7.587] | | 0.667*** [9.705] | 0.613*** [8.437] | 0.924*** [8.955] | | 1.235*** [11.040] |
| TCFD | | | -6.592*** [-3.859] | -0.825*** [-3.880] | | | -6.652** [-2.522] | -1.051*** [-3.587] |
| TCFD×C02 | | | | -8.373*** [-6.478] | | | | -14.34*** [-6.800] |
| SIZE | | -0.681*** [-6.273] | -0.335*** [-2.838] | -0.0772 [-0.539] | | -1.066*** [-5.953] | -0.491*** [-2.632] | -0.0693 [-0.293] |
| AGE | | -0.149*** [-3.428] | -0.142*** [-2.822] | -0.135*** [-3.057] | | -0.284*** [-3.823] | -0.271*** [-3.299] | -0.263*** [-3.460] |
| CF | | -3.851*** [-2.665] | -2.467*** [-2.851] | -3.729** [-2.518] | | -7.616*** [-3.902] | -5.439*** [-4.580] | -7.572*** [-3.793] |
| LEV | | 5.303*** [10.834] | -0.392 [-0.046] | 5.109*** [10.202] | | 1.034*** [14.309] | -0.284 [-0.234] | 1.039*** [13.961] |
| CAPE | | -1.949*** [-10.482] | -0.164 [-0.519] | -1.904*** [-10.143] | | -3.403*** [-12.867] | -0.299 [-0.673] | -3.385*** [-12.635] |
| PPE | | -1.477*** [-4.870] | -0.652** [-2.346] | -1.431*** [-4.642] | | -1.658*** [-3.717] | 0.559 [1.383] | -1.462*** [-3.191] |
| GDP | | -0.174*** [-7.576] | -0.124*** [-3.178] | 0.809 [0.213] | | -0.279*** [-9.063] | -0.248*** [-4.246] | 0.026 [0.446] |
| IQ | | -2.336*** [-10.948] | -1.896*** [-7.215] | -1.039*** [-3.640] | | -4.710*** [-13.058] | -3.996*** [-9.729] | -2.641*** [-5.685] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 29,985 | 29,985 | 29,985 | 20,207 | 29,985 | 29,985 | 29,985 | 20,207 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel C: The joint effect of TCFD and CCE on financial outcomes

| Variable | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] | [Model 9] |
|-------------------------|----------------------|------------------------|------------------------|---------------------|----------------------|------------------------|----------------------|----------------------|-----------------------|
| | KZ Index | KZ Index | KZ Index | WW Index | WW Index | WW Index | ROE | ROE | ROE |
| CCE | 0.0421*** [4.116] | 0.0341*** [3.910] | 0.0375*** [3.965] | 0.0185** [2.173] | 0.0206** [2.349] | 0.0217** [2.163] | -0.062** [-2.485] | -0.060** [-2.404] | -0.065*** [-2.588] |
| TCFD | | -0.0576*** [-3.583] | -0.0557*** [-3.265] | | -2.497** [-2.021] | -0.953 [-0.692] | | 0.0103* [1.877] | 0.0111** [2.014] |
| TCFD×CCE | | | -0.0239*** [-5.288] | | | -0.0132*** [-3.021] | | | 0.0208* [1.796] |
| Constant | 2.883*** [13.490] | 2.767*** [13.474] | 1.976*** [8.471] | -0.0869 [-0.674] | -0.349* [-1.907] | -0.324 [-1.456] | 0.0730* [1.787] | 0.0770* [1.885] | 0.117** [2.499] |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Sector FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observation | 17,488 | 17,488 | 17,488 | 20,449 | 20,449 | 20,449 | 16,313 | 16,312 | 16,259 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 9: Robustness test - Excluding U.S.

| Variable | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] | [Model 9] | [Model 10] | [Model 11] | [Model 12] | [Model 13] | [Model 14] | [Model 15] | [Model 16] |
|-------------------------|---------------------|---------------------|-----------------------|-----------------------|----------------------|----------------------|-----------------------|-----------------------|------------------------|-----------------------|----------------------|-----------------------|-----------------------|----------------------|----------------------|-----------------------|
| | PD-1m | PD-1m | PD-1m | PD-1m | CDS | CDS | CDS | CDS | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | ROA | ROA | ROA | ROA |
| Constant | 0.234*** [4.954] | 0.601*** [3.777] | 0.755** [2.399] | 0.502*** [3.404] | 0.265*** [4.767] | 0.359** [2.523] | 0.467* [1.863] | 0.300*** [2.679] | 1.138*** [11.041] | 3.425*** [22.050] | 11.07*** [12.047] | 5.922*** [10.973] | 1.856*** [16.716] | 34.41*** [13.869] | 0.0299*** [3.334] | 1.564*** [13.337] |
| CCE | 0.0281** [2.429] | 0.0268** [2.471] | | 0.128*** [5.599] | 0.0175*** [2.759] | 0.0211*** [3.112] | | 0.0747*** [5.098] | -0.0125*** [-3.104] | -0.041*** [-2.897] | | -0.0510** [-2.205] | -0.114*** [-5.665] | -0.093** [2.488] | | -0.181*** [-4.681] |
| TCFD | | | -1.224*** [-5.948] | -0.647*** [-2.943] | | | -8.364*** [-5.119] | -0.316** [-2.307] | | | 1.736*** [3.643] | 3.616** [3.289] | | | 0.327*** [6.761] | 0.320*** [10.206] |
| TCFD×CCE | | | | -3.377*** [-5.001] | | | | -1.803*** [-4.149] | | | | 1.122** [2.490] | | | | 5.174*** [4.266] |
| Control variables | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Year FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Sector FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Country FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 23,224 | 23,224 | 23,224 | 23,224 | 23,224 | 23,224 | 23,224 | 23,224 | 23,134 | 23,134 | 23,134 | 23,134 | 23,224 | 23,224 | 23,224 | 23,224 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 10: Channel analysis - Countries' framework

Panel A: The joint effect of TCFD and climate change exposure on firms' default risk under different legal systems

| Variable | Common law countries | | | | Civil Law Countries | | | |
|--------------------|----------------------|-----------------------|-----------------------|-----------------------|----------------------|-----------------------|-----------------------|-----------------------|
| | [Model 1] | [Model 2] | [Model 3] | [Model 4] | [Model 5] | [Model 6] | [Model 7] | [Model 8] |
| | PD-1m | PD-1m | PD-1m | PD-1m | PD-1m | PD-1m | PD-1m | PD-1m |
| Constant | 0.212*** [7.101] | 1.656*** [3.949] | 1.551*** [3.490] | 1.469*** [3.291] | 0.248*** [16.906] | 0.215* [1.971] | 0.852** [2.021] | 0.376** [2.290] |
| CCE | 0.411 [1.516] | 0.298 [1.379] | | 0.593 [0.848] | 0.314*** [2.962] | 0.187** [1.993] | | 0.619*** [3.547] |
| TCFD | | | 3.267 [0.862] | -0.994* [-1.671] | | | -1.078*** [-3.857] | -5.576*** [-3.143] |
| TCFD×CCE | | | | -0.984 [-0.441] | | | | -1.391*** [-2.752] |
| SIZE | | -0.497*** [-2.982] | -0.530** [-2.455] | -0.401** [-2.264] | | 0.385 [0.388] | -0.622*** [-3.069] | -0.333** [-2.434] |
| AGE | | -0.626 [-0.519] | -0.661 [-0.736] | -0.943 [-0.664] | | -0.107** [-2.507] | -0.124* [-1.683] | -0.960** [-2.255] |
| CF | | -0.211 [-0.510] | -0.309* [-1.721] | -0.206 [-0.475] | | -0.288** [-2.453] | -0.879*** [-4.765] | -0.297** [-2.539] |
| LEV | | 0.094 [0.761] | -0.091 [-0.064] | -0.016 [-0.119] | | 0.432*** [9.912] | 0.658*** [8.794] | 0.450*** [10.318] |
| CAPE | | -2.100*** [-4.381] | -0.766 [-0.146] | -2.021*** [-4.063] | | -1.153*** [-6.723] | -2.099*** [-7.920] | -1.191*** [-6.927] |
| PPE | | -0.506*** [-7.600] | -0.346*** [-7.597] | -0.527*** [-7.567] | | 0.471* [1.920] | -0.114** [-2.253] | 0.294 [1.176] |
| GDP | | -0.267*** [-3.923] | -0.366*** [-4.180] | -0.298*** [-3.958] | | -0.102*** [-5.645] | 0.106 [1.608] | 0.845 [0.213] |
| IQ | | -0.344*** [-3.017] | -0.269*** [-3.389] | -0.324*** [-2.671] | | -0.196*** [-9.944] | -0.813* [-1.725] | -0.121*** [-3.862] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 14,058 | 14,058 | 14,058 | 14,058 | 18,862 | 18,862 | 18,862 | 18,862 |
| (Prob > χ^2) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel B: The joint effect of TCFD and climate change exposure on firms' default risk under different legal systems

| Variable | Common law countries | | | | Civil Law Countries | | | |
|-------------------------|----------------------|-----------------------|-----------------------|-----------------------|----------------------|------------------------|-----------------------|-----------------------|
| | [Model 9] | [Model 10] | [Model 11] | [Model 12] | [Model 13] | [Model 14] | [Model 15] | [Model 16] |
| | CDS | CDS | CDS | CDS | CDS | CDS | CDS | CDS |
| Constant | 0.232*** [5.989] | 1.201*** [4.428] | 1.502*** [4.927] | 1.087*** [4.077] | 0.299*** [21.333] | 0.0364** [2.157] | 0.751** [2.229] | 0.504*** [2.756] |
| CCE | 0.285* [1.922] | 0.220*** [2.797] | | 0.378 [0.907] | 0.190*** [3.127] | 0.149** [1.809] | | 0.480*** [4.451] |
| TCFD | | | 3.564 [1.369] | -0.914** [-2.575] | | | -9.547*** [-4.281] | -5.062*** [-4.561] |
| TCFD×CCE | | | | -0.508 [-0.381] | | | | -1.067*** [-3.418] |
| SIZE | | -0.326*** [-3.676] | -0.445*** [-2.986] | -0.267** [-2.516] | | -0.108*** [-3.981] | -0.543*** [-3.349] | -0.377*** [-4.383] |
| AGE | | -0.552** [-2.057] | -0.718 [-1.143] | -0.826 [-0.972] | | -0.808*** [-5.437] | -0.861 [-1.460] | -0.689** [-2.566] |
| CF | | -0.378** [-2.475] | -0.362*** [-3.224] | -0.409 [-1.580] | | -0.235*** [-3.274] | -0.663*** [-4.597] | -0.241*** [-3.338] |
| LEV | | 0.213** [2.245] | -0.114 [-0.127] | 0.153* [1.927] | | 0.344*** [4.178] | 0.531*** [9.012] | 0.356*** [13.186] |
| CAPE | | -1.548*** [-3.826] | -0.631 [-0.192] | -1.510*** [-5.089] | | -0.939*** [-6.103] | -1.696*** [-8.137] | -0.955*** [-8.965] |
| PPE | | -0.360*** [-3.253] | -0.248*** [-8.057] | -0.374*** [-8.983] | | -0.447** [-2.522] | -0.963** [-2.412] | -0.268* [-1.742] |
| GDP | | -0.201*** [-5.124] | -0.297*** [-5.056] | -0.232*** [-5.160] | | -0.078*** [-5.914] | 0.011** [2.147] | 0.205 [0.833] |
| IQ | | -0.272*** [-3.068] | -0.311*** [-5.784] | -0.251*** [-3.472] | | -0.154*** [-10.144] | -0.0385 [-1.023] | -0.867*** [-4.429] |
| Year FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Sector FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Country FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 14,058 | 14,058 | 14,058 | 14,058 | 18,862 | 18,862 | 18,862 | 18,862 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel C: The joint effect of TCFD and climate change exposure on firm value (Tobin's Q) under different legal systems

| Variable | Common law countries | | | | Civil Law Countries | | | |
|-------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|
| | [Model 17] | [Model 18] | [Model 19] | [Model 20] | [Model 21] | [Model 22] | [Model 23] | [Model 25] |
| | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q | Tobin's Q |
| Constant | 1.259*** [3.732] | 2.898*** [4.258] | 15.52*** [3.754] | 6.673*** [10.184] | 1.124*** [8.359] | 3.475*** [7.131] | 9.747*** [8.129] | 6.327*** [9.057] |
| CCE | -0.177*** [-3.808] | -0.161*** [-2.904] | | -0.727** [-2.485] | -0.153*** [-3.011] | -0.606*** [-20.004] | | -0.890*** [-3.039] |
| TCFD | | | 4.069*** [5.014] | 3.386*** [7.544] | | | 1.042* [1.690] | 5.545** [2.672] |
| TCFD×CCE | | | | 1.093 [1.233] | | | | 1.860** [2.213] |
| SIZE | | -0.615*** [-7.322] | -0.582*** [-9.831] | -0.261*** [-7.896] | | -0.110*** [-67.298] | -0.299*** [-5.187] | -0.203*** [-6.110] |
| AGE | | -0.118 [-0.195] | -0.333 [-0.727] | -0.249 [-1.196] | | -0.239** [-2.221] | -0.814** [-2.024] | -0.315** [-2.074] |
| CF | | -0.022 [-0.292] | 1.099*** [7.254] | 0.532*** [3.406] | | 0.508*** [7.800] | 0.533** [2.369] | 0.890*** [4.701] |
| LEV | | -0.515 [-0.168] | -0.171 [-1.201] | 0.943 [1.295] | | -0.114*** [-8.434] | -0.496*** [-4.668] | -0.235*** [-2.932] |
| CAPE | | 0.653*** [6.713] | 0.873* [1.675] | 1.059*** [4.616] | | 2.391*** [34.196] | 1.431*** [3.889] | 2.842*** [8.753] |
| PPE | | -0.444** [-2.536] | -0.199*** [-3.005] | -0.130*** [-2.975] | | -0.131*** [-17.417] | -0.308*** [-4.430] | -0.258*** [-6.041] |
| GDP | | 0.846*** [7.604] | 0.827*** [4.854] | 0.621*** [6.490] | | 0.814*** [10.710] | 0.349*** [2.765] | 0.149** [2.077] |
| IQ | | 0.212*** [5.231] | 1.128*** [6.226] | 0.411*** [3.691] | | -0.348 [-0.094] | 0.511*** [3.691] | -0.158 [-0.094] |
| Year FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Sector FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Country FE | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 14,058 | 14,058 | 14,058 | 14,058 | 12096 | 7922 | 15052 | 10242 |
| (Prob >χ ²) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Panel D: The joint effect of TCFD and climate change exposure on ROA under different legal systems

| Variable | Common law countries | | | | Civil Law Countries | | | |
|--------------------|-----------------------|----------------------|----------------------|-----------------------|-----------------------|------------------------|------------------------|-----------------------|
| | [Model 24] | [Model 26] | Model 27] | [Model 28] | [Model 29] | [Model 30] | [Model 31] | [Model 32] |
| | ROA | ROA | ROA | ROA | ROA | ROA | ROA | ROA |
| Constant | 2.294*** [9.951] | 26.41*** [3.748] | 0.148*** [8.520] | 0.694** [2.544] | 1.945*** [12.681] | 8.743*** [8.365] | 0.0344*** [95.258] | 1.652*** [17.059] |
| CCE | -0.540*** [-3.838] | -0.440** [-2.376] | | -1.326*** [-3.743] | -0.843*** [-4.054] | -0.157*** [-24.919] | | -0.118*** [-2.942] |
| TCFD | | | 4.985*** [15.046] | 0.314 [1.167] | | | 0.106** [1.711] | 0.254*** [7.491] |
| TCFD×CCE | | | | 3.309*** [2.786] | | | | 3.142** [2.515] |
| SIZE | | 1.164*** [3.680] | | | | 0.309*** [8.641] | 0.0320*** [8.025] | 1.394*** [7.815] |
| AGE | | 0.842** [2.546] | 0.104 [0.453] | -0.146 [-0.960] | | 0.258*** [25.556] | 0.605*** [14.471] | 0.444** [2.521] |
| CF | | 5.725 [1.330] | 0.266*** [21.765] | 6.859*** [4.137] | | 3.107*** [3.789] | 0.277*** [7.298] | 0.689 [0.270] |
| LEV | | -1.644 [-0.944] | 0.662 [1.289] | -2.408*** [-3.373] | | -1.647*** [-64.157] | -0.662*** [-80.036] | -0.285*** [-2.809] |
| CAPE | | -0.176 [-0.109] | 0.694*** [3.401] | 0.282 [0.122] | | 4.105*** [3.861] | 0.274*** [8.297] | 2.553*** [6.332] |
| PPE | | 0.166 [0.818] | 0.317*** [4.385] | 0.137 [0.309] | | 0.321*** [22.945] | -0.483 [-0.009] | 0.305*** [5.327] |
| GDP | | -0.125 [-1.212] | 0.572*** [7.977] | 0.239 [0.082] | | 0.561*** [4.913] | 0.341*** [8.385] | 0.636 [1.602] |
| IQ | | 1.813*** [2.825] | 0.162 [1.226] | 3.125*** [3.132] | | 0.142*** [22.125] | 0.842*** [6.331] | 0.343*** [4.598] |
| <i>Year FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Sector FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| <i>Country FE</i> | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Observation | 13,990 | 13,990 | 13,990 | 13,990 | 18,840 | 18,840 | 18,840 | 18,840 |
| (Prob > χ^2) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Appendix A1

| Variables | Definition | Prior research | Data sources |
|-----------------------------|--|--|--|
| Firm value | | | |
| ROA | Net income scaled by total assets | (Aswani et al., 2024) | LSEG (Refinitiv Eikon Database) |
| Tobin's Q | Tobin's Q is calculated by dividing the total market value of equity, the total debt (long-term and short-term debt), and the liquidation value of preferred stocks by the book value of total assets. | (Perdichizzi et al., 2024) (Li et al., 2024; Matsumura et al., 2014) | LSEG (Refinitiv Eikon Database) |
| Firm risk | | | |
| PD (1, 3, 6, 12, 24 months) | The default probability (PD) is calculated using the cumulative distribution function of a standard normal distribution, denoted by F(DTD). The PD is estimated for a range of time horizons, including 3 to 6 months. | (Do, 2022) | |
| PD-1Y, 2Y | Default Probability (DP): The Credit Research Initiative (CRI) probability of default with 1, and 2-year prediction horizon. | (Do, 2022) | The Risk Management Institute (RMI) is affiliated with the National University of Singapore and can be accessed at https://rmicri.org/en/about/ |
| CDS | Credit default swap (CDS) spread represents the fixed premium paid by the protection buyer to the protection seller for a specified period. This premium is received in exchange for compensation in the event of a credit event, thereby reflecting default risk in a straightforward manner (Callen et al., 2009). | | |
| DTD | Distance to default (DTD) The distance to default is defined as $DTD_t = \frac{\ln\left(\frac{V_t}{F + \delta L}\right) + \left(\mu_v - \frac{\xi_v^2}{2}\right)\tau}{\xi_v \sqrt{\tau}}$ | Duffie et al. (2007), Duan et al. (2012), and (Do, 2022) | |

Where V : The market value of the firm's assets at time t ; F : represents the firm's debt at time t (typically proxied by short-term and a portion of long-term liabilities);

L is an additional liability or obligation that is not captured in F .

δ : a fraction adjusting the contribution of the additional liabilities to the default point;

μ_v Expected return on the firm's assets (drift term).

ξ Volatility of the firm's assets, reflecting uncertainty in asset values. τ time horizon over which default risk is evaluated.

Independent variables

| | | | |
|-----------------------|---|---|---|
| CCE | Firm-level climate change exposure: The levels of a firm's exposure to climate change shocks regard the regulatory (RGE), physical (PHE), and opportunity (OPE). A firm with high CCE value indicates more significant exposure to climate risks related to opportunities, regulations, and physical shocks. | (Sautner et al., 2023a) | (Climate risk) constructed and provided using Bigram analysis on quarterly earnings conference calls by Sautner et al. (2022) https://osf.io/fd6jq/files/osfstorage?view_only= |
| CRI | The climate risk score is calculated as a weighted average of critical measures: total mortality, mortality rate per 100,000 individuals, total economic losses, and losses relative to GDP. According to Huang et al. (2018), this score is subjected to a multiplication factor of -0.1 to facilitate meaningful interpretation across diverse contexts, implying a correlation where higher values indicate increased climate vulnerability. | (Chang et al., 2024; Ding et al., 2021; Huang et al., 2018) | Germanwatch's 2006–2020 editions |
| CO₂ | Total carbon dioxide (CO ₂) and CO ₂ equivalents emission in tonnes for scope 1,2 and 3. | (Cohen et al., 2023; Matsumura et al., 2014) | LSEG (Refinitiv Eikon Database) |
| TCFD | Dummy variable indicating if a company is a TCFD supporter as reported by TCFD. Companies support a commitment to implementing TCFD recommendations, which | (Bingler et al., 2024) | LSEG (Refinitiv Eikon Database) |

| | | | |
|---|--|---|---------------------------------|
| | signifies the company’s intent to analyze climate-related risks and opportunities and disclose climate-related information according to the TCFD framework. Therefore, this study assumes that if a company declares support for TCFD and its recommendations, it provides climate-related information for stakeholders in the market. | | |
| High Emission | High Emission is a dummy variable equal to one for carbon-intensive firms and zero otherwise | (Kabir et al., 2021) | LSEG (Refinitiv Eikon Database) |
| <i>Firm control variables</i> | | | |
| SIZE | Firm size is measured as the natural logarithm of total book assets (in millions of USD). | | LSEG (Refinitiv Eikon Database) |
| AGE | Firm age is measured by the logarithm of the number of years each enterprise has been listed. | | LSEG (Refinitiv Eikon Database) |
| CF | CF is calculated by operating cash flows divided by total book assets. | | LSEG (Refinitiv Eikon Database) |
| LEV | Corporate leverage is measured as total long-term and short-term debt divided by total book assets. | | LSEG (Refinitiv Eikon Database) |
| CAPE | The ratio of capital expenditure to the sales revenue of firm <i>i</i> in year <i>t</i> . | | LSEG (Refinitiv Eikon Database) |
| PPE | Property, Plant and Equipment scaled by total assets. | | LSEG (Refinitiv Eikon Database) |
| <i>Country control variables</i> | | | |
| GDP | The annual GDP growth rate equals the percentage change of GDP per year. | (Feng et al., 2024; Trinh et al., 2024) | World Bank database |

| | | | |
|--|--|------------------------|---------------------|
| IQ | <p>This study derives the institutional quality (IQ) variable by taking the average of primary indicators proposed by Kaufmann et al. (2009):</p> | Kaufmann et al. (2009) | World Bank database |
| | <p><i>The effectiveness of government:</i> Evaluate public service quality, civil service independence, policy implementation, and government credibility.</p> | | |
| | <p><i>Voice and Accountability:</i> Refers to the capacity of citizens to select their government and the existence of freedoms.</p> | | |
| | <p><i>Regulatory Effectiveness:</i> Assess the government's ability to design and enforce policies that foster private sector growth.</p> | | |
| | <p><i>Legal Framework:</i> Assess trust in laws, contract enforcement, property rights, and the effectiveness of the judiciary and law enforcement.</p> | | |
| | <p><i>Control of Corruption:</i> Examines public trust in governance and the degree to which corruption is minimized.</p> | | |
| <p><i>Political stability:</i> Measures the risk of government destabilization due to violence or terrorism.</p> | | | |
