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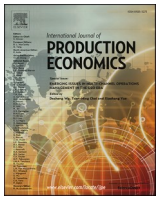
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The impact of firm-specific climate change exposure on vertical integration

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ABSTRACT

Firm-specific climate change exposure, which captures market perceptions of climate change-related risks and opportunities faced by a firm, has important implications for firm decisions. However, it remains unclear how such exposure may affect firms' buy-versus-make decisions in supply chains. Our study addresses this research gap by drawing on the theoretical lens of Transaction Cost Economics (TCE) to examine vertical integration as a strategic response to firm-specific climate change exposure. Following the TCE logic, we further investigate the moderating roles of geographic diversity and financial stability. Using panel data from 1395 publicly listed U.S. manufacturing firms from 2007 to 2020, our analysis shows that firms with higher climate change exposure are more likely to pursue vertical integration. Moreover, this effect is stronger for firms with more geographically dispersed operations and greater financial stability. Overall, our findings highlight the importance of perception-based climate change exposure in shaping firms' boundary decisions, providing important implications for both research and managerial practices.

1. Introduction

Climate change is increasingly disrupting firms' operations by raising uncertainties across supply networks, logistics systems, and the broader conditions under which inter-firm transactions are organized (Ignatius et al., 2024; Wang et al., 2015). For instance, physical shocks such as floods and heatwaves can interrupt production, undermine operational performance, and expose firms to greater coordination challenges (Feng et al., 2025; Liang et al., 2024). At the same time, climate change-induced regulatory changes (e.g., carbon pricing schemes, disclosure requirements, and carbon taxes) further heighten uncertainties for firms by making future compliance costs and enforcement practices difficult to anticipate (Calzolari et al., 2025; Deng et al., 2025).

Accordingly, prior research has extensively examined how firms respond to these climate change-related challenges (Hou et al., 2025; Pankratz and Schiller, 2024). For instance, firms can adapt through internal strategies, such as green innovation and green finance (Fatica and Panzica, 2021; Su and Moaniba, 2017), or through inter-firm coordination, such as green supply chain collaboration (Lerman et al., 2022). While these studies provide important insights into how exogenous climate change-related events affect firms' response strategies, firms do not respond solely to such exogenous shocks. Instead, their responses are also shaped by how climate-related risks and opportunities are interpreted by external market participants, such as investors and financial analysts (Huang et al., 2022; Sautner et al., 2023a, 2023b). In particular, these external market participants influence firms' decision-making by affecting their access to financing, how risky they are perceived to be, and expectations about their future performance (Feng et al., 2024; Javadi and Masum, 2021). As a result, firms may adjust their strategies not only in response to actual climate change-related events, but also in response to how these events are interpreted and evaluated by the market.

Such interpretations of climate change-related risks and opportunities by market participants are captured by firm-specific climate change exposure (Sautner et al., 2023a, 2023b). Empirically, this measure is constructed using textual analysis of earnings call transcripts, capturing the extent to which managers and financial analysts discuss

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climate change-related topics (Cepni et al., 2024; Sautner et al., 2023a). As such, firm-specific climate change exposure reflects how external stakeholders perceive the impact of climate change on firms, serving as an important stakeholder-based signal that shapes managerial decision-making (Ginglinger and Moreau, 2023; Tian and Zhao, 2025). Given this, prior studies have highlighted the importance of firm-specific climate change exposure (Sautner et al., 2023a, 2023b). However, how such perception-based exposure by market participants shapes firms' strategic responses remains unclear. We intend to address this gap by examining how firm-specific climate change exposure influences firms' boundary decisions.

With regard to firms' strategic responses, prior research suggests that firms typically adjust internal activities or strengthen inter-firm collaboration (Lerman et al., 2022; Liu et al., 2020). It should be noted that firms may also reconfigure their organizational boundaries through vertical integration of upstream or downstream activities in response to external environmental changes (Harryson and Lorange, 2024; Serohi, 2022). This is because such vertical integration allows firms to gain greater control over coordination, reduce dependence on external partners, and better manage climate-related risks across the value chain (Franco et al., 2024; Meng et al., 2018). Yet, it remains unclear whether firm-specific climate change exposure leads firms to adopt vertical integration as a strategic response.

Accordingly, our study aims to examine whether firms vertically integrate in response to firm-specific climate change exposure. Moreover, we also argue that this effect is likely to depend on firm-specific contingencies. In this study, we focus on the moderating effects of geographic diversity and financial stability. Firms operating across multiple regions face fragmented regulations, uneven climate shocks, and more complex supply chains, which increase coordination and contracting costs (Chen et al., 2022; Choi and Krause, 2006). As a result, firms with greater geographic diversity are more likely to adopt vertical integration to mitigate these challenges. At the same time, vertical integration requires substantial financial resources, including upfront investments and ongoing governance costs (Franco et al., 2024; Lafontaine and Slade, 2007). Firms with stronger and more stable financial resources are better able to bear these costs and internalize activities (Julian & Ofori-dankwa, 2013; Sheng and Ding, 2024). Thus, we also expect that the effect of firm-specific climate change exposure on vertical integration will be stronger among firms with greater geographic diversity and higher financial stability. Fig. 1 illustrates our proposed conceptual model. Building on this, our study aims to answer the following two important research questions:

1. Do firms vertically integrate in response to firm-specific climate change exposure?
2. How do geographic diversity and financial stability moderate the relationship between firm-specific climate change exposure and vertical integration?

To empirically investigate the above research questions, we constructed a panel dataset of 1395 U.S. publicly listed manufacturing firms (SIC codes 20–39) covering the period from 2007 to 2020. We first collected financial data for these firms from Compustat to construct firm-level and industry-level variables. We then merged these data with firm-specific climate change exposure measures from Sautner et al. (2023a) and vertical integration data from the Frésard–Hoberg–Phillips Vertical Relatedness Data Library (Frésard et al., 2020). Based on this sample, we employed a two-way fixed effects regression model to test our hypotheses. The results show that firm-specific climate change exposure is positively associated with vertical integration. Moreover, this effect is stronger among firms with greater geographic diversity and higher financial stability.

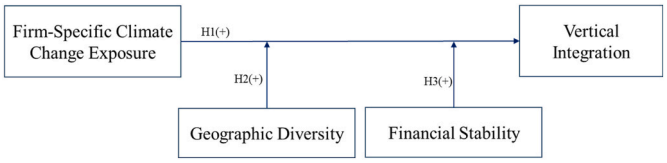


Fig. 1. Conceptual framework.

Our study contributes to both the literature and managerial practice in the following ways. First, we provide important empirical evidence that firm-specific climate change exposure, as perceived by market participants, shapes firms' boundary decisions. In particular, we provide important empirical evidence that market-based evaluations of climate change impacts lead firms to internalize inter-organizational relationships through vertical integration. By doing so, our study shifts the focus from exogenous climate shocks to perception-based signals as a driver of firms' boundary choices.

Second, we contribute to the literature on vertical integration by identifying the important firm-level contingencies that condition the relationship between climate change exposure and boundary decisions. Specifically, our findings show that the effect of climate change exposure on vertical integration is more pronounced among firms with greater geographic diversity and higher financial stability. These findings suggest that firms' internalization decisions are not uniform but depend on both the complexity of their operational environments and their ability to mobilize the financial resources required for vertical integration. In this way, we provide a more nuanced understanding of when firms adjust their boundaries in response to environmental uncertainty.

Finally, our study offers managerial implications by highlighting that firms' strategic boundary choices are shaped not only by actual climate change exposure but also by how such exposure is perceived by the market. This insight highlights the importance for managers of actively monitoring and responding to external market evaluations.

2. Literature review and hypothesis development

2.1. Firm-specific climate change exposure: its impacts and corporate responses

Firm-specific climate change exposure captures how market participants perceive the climate-related risks and opportunities faced by a firm (Sautner et al., 2023a, 2023b). More specifically, it reflects how external market participants (e.g., financial analysts) evaluate the extent to which climate-related factors may affect a firm's future operations and performance (Cepni et al., 2024; Sautner et al., 2023b). These evaluations are shaped by the dual nature of climate change, which introduces both risks and opportunities for firms (Fan and Zhao, 2025; Flammer et al., 2021; Huang et al., 2022; Javadi and Masum, 2021). On the one hand, physical risks associated with climate change can disrupt production and increase operating costs (Zhang et al., 2018), leading external market participants to perceive greater uncertainty. On the other hand, climate change also creates new market opportunities, particularly through the transition toward a low-carbon economy, which may be interpreted as potential sources of future growth.

Existing studies have primarily examined the firm-level outcomes of climate change exposure (Lu et al., 2019; Zhang et al., 2018). For instance, prior research shows that physical risks reduce productivity across industries (Lu et al., 2019; Song et al., 2022; Zhang et al., 2018). In addition, transition and reputational risks increase financing constraints by raising borrowing costs and tightening lending conditions (Hrazdil et al., 2024; Huang et al., 2022; Javadi and Masum, 2021). These pressures can even increase the likelihood of bankruptcy (Feng et al., 2024). Accordingly, financial markets respond by adjusting portfolios and pricing climate-related risks, particularly those associated with regulation (Choi et al., 2020; Faccini et al., 2023; Stroebel and Wurgler, 2021).

In response to these pressures, firms adopt various strategies within

their organizational boundaries. They increase the use of green finance instruments, such as green bonds, to support emission reduction and sustainability goals (Chen et al., 2024; Fatica and Panzica, 2021; Irfan et al., 2022). They also invest in green innovation, which improves energy efficiency and enables firms to capture opportunities associated with the low-carbon transition (Liu et al., 2024; Su and Moaniba, 2017). In addition, firms strengthen governance and disclosure practices to enhance environmental accountability, for example through board composition and climate-related reporting (Ben-Amar et al., 2017; Nadeem et al., 2020; Nuber and Velte, 2021).

However, despite these insights, existing studies largely focus on the direct effects of climate-related events on firm performance and strategic responses. As a result, there is limited attention to the outcomes of climate change exposure as perceived by market participants. It thus remains unclear how such perceived exposure influences firms' strategic responses and governance decisions. This gap is important because prior research suggests that perceived climate change exposure can shape managerial decisions and investor expectations (Feng and Zhu, 2024; Sautner et al., 2023b). Moreover, existing studies have paid little attention to how such perception-driven exposure affects inter-organizational responses, such as vertical integration. We thus aim to address this important research gap by examining how firm-specific climate change exposure influences firms' vertical integration decisions.

We summarize the relevant literature in Table 1 to highlight how our study differs from prior research. Overall, rather than focusing on environmental policy shocks (e.g., carbon taxes or regulations), we examine firm-specific climate change exposure as perceived by market participants and its impact on firms' strategic responses. In particular, we focus on how this perception shapes firms' vertical integration and organizational boundary decisions. By doing so, we extend the existing literature by providing new insights into how market-perceived climate risks influence firms' governance choices.

2.2. The impact of firm-specific climate change exposure on vertical integration

Our study adopts the lens of Transaction Cost Economics (TCE) to explain how firm-specific climate change exposure affects firms' vertical integration decisions. TCE examines how firms adjust governance structures and organizational decisions to minimize transaction costs (Ketokivi and Mahoney, 2020). Such transaction costs are a key driver for a firm's "make-or-buy" decision, determining whether the firm internalizes activities or relies on external upstream and downstream partners (Jacobides, 2008; Ketokivi and Mahoney, 2020). Building on this perspective, we argue that firm-specific climate change exposure increases transaction-related uncertainties in exchange relationships. Such uncertainties make it more difficult for focal firms to specify and enforce complete contracts, thereby heightening the risk of opportunistic behavior and increasing transaction hazards. As a result, these conditions increase transaction costs and prompt firms to internalize transactions through vertical integration to better mitigate these uncertainties.

First, firm-specific climate change exposure amplifies transaction-related uncertainty for firms. From an external institutional perspective, greater climate change exposure increases uncertainty regarding regulatory trajectories, as evolving climate policies may alter compliance requirements across exchange partners (Bui and De Villiers, 2017; Engau and Hoffmann, 2011). Such exposure also accelerates technological change and requires firms to continuously update their capabilities to keep pace with industry developments (Ferreira et al., 2020; Pinkse and Kolk, 2010). From an internal operations perspective, climate change exposure heightens the likelihood of disruptions to production and logistics, which lead to fluctuations in the availability of critical inputs (Ali et al., 2023; Ghadge et al., 2020). As a result, high climate change exposure makes it more difficult for firms to specify and maintain stable contractual terms with exchange partners (Dahlmann

Table 1
Climate change-related studies.

Representative Studies	Research Aim	Method	Climate Change Focus	Response Focus
Sautner et al. (2023a)	To measure firm-level climate risks and opportunities perceived by market participants	Textual analysis	Climate change exposure as perceived by market participants	None
Hrazdil et al. (2024)	To examine how adverse climate incidents affect firms' bank loans	Empirical study	Physical climate shocks	None
Liang et al. (2024)	To investigate how extreme weather affects firms' operational performance	Empirical study	Physical climate shocks	None
Fatica and Panzica (2021)	To examine whether issuing green bonds reduces firms' carbon emissions and improves issuers' environmental engagement	Empirical study	Carbon emissions	None
Liu et al. (2024)	To examine whether digital technology reduces carbon emissions in Chinese cities and through what mechanisms this effect operates	Empirical study	Carbon emissions	None
Li (2025)	To examine whether and how firms adapt to physical exposures to climate change	Empirical study	Physical climate shocks	Internal adaptation practices
Fan and Zhao (2025)	To examine whether firms' awareness of climate risks and opportunities influences their carbon management practices, and whether such practices improve carbon reduction performance	Empirical study	Corporate awareness of climate change risk and opportunity	Internal carbon management practices
Lee and Klassen (2016)	To examine whether firms differ in adopting and implementing carbon management practices in response to the	Empirical study	Global warming issue	Internal carbon management practices

(continued on next page)

Table 1 (*continued*)

Representative Studies	Research Aim	Method	Climate Change Focus	Response Focus
	global warming issue.			
Fritsch et al. (2025)	To examine firms' trade-offs in their voluntary disclosure decisions following negative media coverage of climate change incidents.	Empirical study	Climate change incidents	Climate change information disclosure
Meng et al. (2018)	To examine how carbon tax affects a manufacturer's make-or-buy decision	Analytical study	Climate related regulatory shocks	Vertical integration
Our study	To investigate how firm-specific climate change exposure drives vertical integration and cross-firm governance restructuring along the value chain	Empirical study	Climate change exposure as perceived by market participants	Vertical integration

and Roehrich, 2019; Wever et al., 2012).

Moreover, these increased transaction-related uncertainties further lead to transaction hazards in exchange relationships. Under high levels of firm-specific climate change exposure, firms face greater difficulty in anticipating future contingencies and fully specifying contractual terms. As a result, exchange partners may exploit such contractual incompleteness to pursue self-interest, such as renegotiating prices when conditions change (Cuypers et al., 2021). In addition, these uncertainties can give rise to hold-up problems when transactions involve large asset-specific investments (Hallikas et al., 2002). Asset specificity refers to investments in production processes, technologies, or supplier relationships that are tailored to particular transactions and cannot be easily redeployed to alternative partners (Lee, 2022; Lui et al., 2009). In particular, when firms make such investments under high climate change exposure, they become more dependent on exchange partners, which increases the likelihood of opportunistic renegotiation.

In this context, vertical integration serves as an effective governance response to reduce transaction costs associated with climate change exposure. In our study, vertical integration refers to the ownership-based internalization of upstream or downstream activities within a firm's organizational boundary (Frésard et al., 2020; Helfat and Campo-Rembado, 2016). By bringing these exchange activities under internal ownership, firms replace market-based transactions with hierarchical governance, which reduces the transaction costs associated with opportunistic behavior and contractual disputes. In addition, vertical integration allows firms to exercise greater control over specialized assets and reduce dependence on external partners, which lowers the costs of monitoring, renegotiation, and contract enforcement (Acemoglu et al., 2009; Lin et al., 2014). As a result, vertical integration helps firms effectively reduce transaction costs that arise under heightened uncertainty and transaction hazards associated with greater climate change exposure.

Accordingly, we expect that firms facing higher levels of firm-specific climate change exposure are more likely to pursue vertical integration as a strategic governance response.

H1. Firm-specific climate change exposure positively affects firms' vertical integration.

2.3. The moderating role of geographic diversity

Geographic diversity refers to the extent to which a firm's production and operational activities are distributed across multiple geographic regions (Fan and Xiao, 2023). From a TCE perspective, we argue that geographic diversity strengthens the positive relationship between firm-specific climate change exposure and vertical integration by amplifying transaction costs in exchange relationships. Specifically, geographic diversity exacerbates the transaction-related uncertainties associated with climate change exposure, making it more difficult for firms to manage exchange relationships efficiently.

First, geographic diversity contributes to contractual incompleteness and higher transaction costs under firm-specific climate change exposure. Firms operating across multiple regions face heterogeneous and evolving regulatory environments, including differences in carbon pricing, emission standards, and policy enforcement (Fan et al., 2022; Nippa et al., 2021). As a result, firms face greater difficulty in specifying and enforcing consistent contractual terms with exchange partners, which increases the likelihood of contractual gaps and disputes (Charpin and Cousineau, 2025).

Second, geographic diversity increases transaction costs by intensifying transaction hazards associated with asset specificity. To adapt to region-specific climate risks, firms often invest in localized infrastructure, technologies, and logistics systems (Li, 2025). Such investments are difficult to redeploy across regions, which increases dependence on local exchange partners. This dependence raises the risk of opportunistic behavior and hold-up, as partners may exploit contractual incompleteness under changing conditions.

Third, geographic diversity increases transaction costs through greater complexity in exchange relationships. Highly dispersed operations involve a larger and more diverse set of partners across regions. This reduces transparency and increases information asymmetry, which makes it difficult for firms to monitor and verify partner performance (Chen et al., 2022; Choi and Krause, 2006). Consequently, a high level of geographic diversity increases the transaction costs associated with coordinating activities, monitoring compliance, and enforcing contractual obligations across exchange partners.

While geographic diversity may increase transaction costs, it may also provide several benefits. For instance, firms operating across multiple regions can accumulate local knowledge about region-specific climate risks and regulatory changes. These information benefits may help them anticipate climate-related challenges, select more reliable exchange partners, and adjust contracts or sourcing arrangements more effectively. As a result, geographically diversified firms may be able to manage climate-related uncertainty without necessarily relying on vertical integration. However, from a TCE perspective, we argue that these informational benefits are likely to be outweighed by the additional transaction costs created by geographic dispersion.

Taken together, geographic diversity amplifies the transaction costs associated with firm-specific climate change exposure by intensifying contractual incompleteness, transaction hazards, and coordination complexity. As these transaction costs rise, firms are more likely to internalize exchange activities through vertical integration in order to mitigate these risks. Accordingly, we propose the following hypothesis:

H2. The positive impact of firm-specific climate change exposure on the extent of vertical integration is more pronounced for firms with greater geographic diversity.

2.4. The moderating role of financial stability

Financial stability refers to the extent to which a firm can maintain

consistent financial performance and sustain the resources required for its operations (Nguyen et al., 2023). A key benefit of high financial stability is that it enables firms to undertake strategic initiatives that require substantial and sustained resource commitments (Julian and Ofori-Dankwa, 2013; Sheng and Ding, 2024).

From a TCE perspective, while vertical integration can reduce external transaction costs by replacing market-based exchanges with internal governance, it is not costless. Vertical integration requires significant upfront asset-specific investments, as well as ongoing costs of coordination, monitoring, and control within the organization (Franco et al., 2024; Lafontaine and Slade, 2007). These internal governance costs are particularly salient under conditions of firm-specific climate change exposure, as firms must continuously adapt internal operations to changing environmental and regulatory conditions (Bui and De Villiers, 2017; Engau and Hoffmann, 2011). As a result, firms with greater financial stability are better positioned to make asset-specific investments, absorb these costs, and sustain ongoing coordination and monitoring required under internal governance.

In contrast, firms with low financial stability face tighter financial constraints and higher costs of capital (Kim and Chae, 2022). These firms have limited capacity to make asset-specific investments and to sustain internal coordination and monitoring costs. For these firms, the internal costs of vertical integration may outweigh its benefits, even when firm-specific climate change exposure increases transaction costs in external markets.

Overall, we argue that financial stability strengthens the positive relationship between firm-specific climate change exposure and vertical integration by shaping their ability to internalize exchange activities. As such, we propose the following hypothesis:

H3. The positive impact of firm-specific climate change exposure on the extent of vertical integration is more pronounced for firms with higher financial stability.

3. Data and methodology

3.1. Data collection

Our sample consists of publicly listed U.S. manufacturing firms over the period 2007–2020. We identify manufacturing firms using two-digit Standard Industrial Classification (SIC) codes ranging from 20 to 39. The sample period begins in 2007, which marks a significant increase in attention to climate change. Specifically, the publication of the IPCC Fourth Assessment Report in 2007 heightened global awareness of climate-related risks. Similarly, the Energy Independence and Security Act, enacted in the same year, strengthened regulatory efforts in the United States to reduce greenhouse gas emissions. The sample period ends in 2020 due to data availability for the vertical integration measure.

Then, we collected financial data for U.S. manufacturing firms from Compustat to construct measures of financial stability, as well as firm-level and industry-level control variables. Following this, we matched these data with firm-specific climate change exposure measures from Sautner et al. (2023a) and vertical integration data from the Frésard–Hoberg–Phillips Vertical Relatedness Data Library (Frésard et al., 2020). After merging these datasets and excluding observations with missing values, the final sample consisted of 1395 firms and 9655 firm-year observations.

3.2. Variable measurements

In this section, we describe the measurements and sources of all variables. Table 2 presents detailed definitions and measurement procedures for each variable.

3.2.1. Firm-specific climate change exposure

We measure firm-specific climate change exposure using the time-varying index developed by Sautner et al. (2023a). This index is constructed from textual analysis of quarterly earnings call transcripts and captures the extent to which climate-related risks and opportunities are discussed by managers and financial analysts. The underlying rationale is that earnings calls reflect real-time interactions between firms and market participants. As such, the climate-related discussions provide a measure of how salient and decision-relevant climate issues are for the firm. The index is based on bigram text analysis of climate-related terms, which captures the relative intensity of climate-related discourse in each call.

Importantly, this measure reflects market participants' perceptions of climate-related risks and opportunities, rather than realized physical or regulatory shocks. From this perspective, both risks and opportunities can contribute to uncertainty for firms. That is, climate-related risks increase uncertainty by making future operating conditions less predictable, while climate-related opportunities (e.g., emerging green technologies or low-carbon policies) introduce uncertainty by requiring firms to adapt to evolving technologies, develop new capabilities, and reconfigure supply chain relationships. Therefore, the firm-specific climate change exposure measure developed by Sautner et al. (2023a) captures the salience of climate-related issues that give rise to overall uncertainty. This measure is also widely used as a proxy for capturing firm-level market attention to climate-related uncertainty and risks in recent studies (e.g., Ginglinger and Moreau, 2023; Sautner et al., 2023b). Based on this measurement, the index ranges from 0 to 1, with higher values indicating greater exposure to climate-related uncertainty. Because the data are reported quarterly, we convert them to annual values by averaging across the four quarters in each year.

Table 2
Variable measurements.

Variable	Measurement	Reference	Source
Vertical Integration	Textual analysis of product description vocabularies. The index has been multiplied by 100 for better visualization of the results in our study.	Frésard et al. (2020)	Frésard-Hoberg-Phillips Vertical Relatedness Data Library
Climate Change Exposure	Relative frequency with which bigrams related to climate change occur in the transcripts of earnings conference calls.	Sautner et al. (2023a)	Sautner et al. (2023a)
Firm Size	The natural logarithm of a firm's total assets.	Frésard et al. (2020)	Compustat
Return on Assets	The ratio of earnings before interest and taxes to total assets.	Chen et al. (2024)	Compustat
Leverage	The ratio of total debt to total assets, where total debt is long-term debt plus debt in current liabilities.	Chen et al. (2024)	Compustat
Quick Ratio	The ratio of current assets minus inventories to current liabilities.	Fan and Xiao (2023)	Compustat
Process Sophistication	The ratio of capital expenditure to total sales.	Dzengelevski et al. (2024)	Compustat
Geographic Diversity	One minus the Herfindahl-Hirschman Index.	Fan and Xiao (2023)	Compustat
Financial Stability	The standard deviation of return on assets over the most recent five years, with reverse coding applied.	Fan and Xiao (2023)	Compustat

3.2.2. Vertical integration

We measure vertical integration at the firm level using the vertical integration data developed by Frésard et al., 2020, who apply textual analysis of product descriptions in 10-K filings. This measure has been widely used in recent studies in operations management (Barker et al., 2022; Fan and Xiao, 2023), finance (Fahlenbrach et al., 2021; Grieser et al., 2022), and strategic management (Runge et al., 2022). In particular, the measure is based on the overlap between a firm's business descriptions and the Bureau of Economic Analysis input-output structure. This mapping allows the measure to determine whether a firm operates in industries that are vertically linked (i.e., where one industry supplies inputs to another). In this way, this measure provides a more detailed view of whether a firm's internal operations span vertically related markets.

While the measure does not directly observe ownership, operating in multiple vertically linked industries is closely associated with vertical integration decisions. When firms report operational activities in both upstream and downstream industries, this typically reflects the internalization of activities that would otherwise be conducted through market transactions. This interpretation is also consistent with prior literature (e.g., Fahlenbrach et al., 2021; Barker et al., 2022), which treats cross-stage presence as a proxy for vertical integration. In fact, Frésard et al. (2020) also validate this measure by showing that it correlates with the use of terms such as "vertical integration" and "vertically integrated" in annual reports. This validation suggests that the measure is able to effectively capture firms' vertical integration. In our sample, the original vertical integration index ranges from 0 to 0.08. To improve interpretability, we multiply the index by 100 in the following regression models.

3.2.3. Moderators

Geographic Diversity. Following previous studies (Fan and Xiao, 2023; Hendricks et al., 2009), we use the Herfindahl-Hirschman Index (HHI) to measure geographic diversity. We collect this segment-level data from the Compustat database and construct the measure as follows.

$$\text{Geographic Diversity} = 1 - \sum_i \left(\frac{IAS_i}{AT}\right)^2, \tag{1}$$

where IAS_i denotes the yearly assets of the ith geographic segment, and AT represents the firm's annual total assets. In addition, we use the number of geographic segments per firm-year as an alternative measure in the robustness tests.

Financial Stability. To capture financial stability, we use the inverse of income stream uncertainty, as higher uncertainty reflects lower stability. Following prior studies (Fan and Xiao, 2023; Miller and Bromiley, 1990), we measure financial stability using the standard deviation of return on assets over a five-year horizon and reverse-code this measure, such that higher values indicate greater financial stability. Additionally, we construct an alternative measurement based on the standard deviation of return on assets over a seven-year horizon and apply the same reverse-coding approach to capture longer-term financial stability.

3.2.4. Control variables

In line with prior studies (Chen et al., 2024; Dzengelevski et al., 2024; Fan and Xiao, 2023; Frésard et al., 2020), we incorporate a set of firm-level control variables that have been documented to be associated with vertical integration, including firm size (the natural logarithm of total assets), return on assets (earnings before interest and taxes divided by total assets), leverage (total debt divided by total assets), quick ratio (current assets minus inventories and then divided by current liabilities) and process sophistication (capital expenditure divided by total sales). That is, firms with larger size and stronger financial performance are generally better positioned to undertake mergers and acquisitions and, therefore, are more likely to vertically integrate. In addition, financial flexibility increases the likelihood of vertical integration, with leverage and the quick ratio capturing firms' financing capacity. Finally, process sophistication reflects the intensity of capital investment in production. Firms that are more vertically integrated often require greater capital investment to manage multiple stages of the production process.

3.3. Estimation methodology

We construct a two-way fixed effects regression model, as shown in Equation (2), to test our hypotheses. We include industry fixed effects (four-digit SIC codes) to control industry-level heterogeneity. This is important because a firm's vertical scope depends on capability differences and transaction costs within the industry (Díez-Vial, 2007; Jacobides, 2008). We also include year fixed effects to control time-specific shocks and unobserved factors that vary over time. These fixed effects are able to mitigate concerns that our results are driven by common temporal shocks or time-invariant industry characteristics. To address potential reverse causality, we lag both the independent variable and the control variables by one year.

$$\begin{aligned} \textit{Vertical Integration}_{i,t+1} &= \beta_0 + \beta_1 \textit{Firm-Specific Climate Change Exposure}_{i,t} \\ &+ \beta_2\, \textit{Firm-Specific Climate Change Exposure}_{i,t} \times \textit{Financial Stability}_{i,t} \\ &+ \beta_3\, \textit{Firm-Specific Climate Change Exposure}_{i,t} \times \textit{Geographic Diversity}_{i,t} \\ &+ \beta_4 \textit{Financial Stability}_{i,t} + \beta_5 \textit{Geographic Diversity}_{i,t} + \textit{Controls}_{i,t} \\ &+ \textit{Industry FE} + \textit{Year FE} + \varepsilon_{i,t} \end{aligned} \tag{2}$$

where $\textit{Vertical Integration}_{i,t+1}$ represents the extent of vertical integration of a firm. $\textit{Firm-Specific Climate Change Exposure}_{i,t}$ refers to the firm's exposure to climate change. $\textit{Financial Stability}_{i,t}$ and $\textit{Geographic Diversity}_{i,t}$ denote the moderating variables. *Controls* is a vector of firm-level control variables. *Industry FE* and *Year FE* represent industry and year fixed effects, respectively, and $\varepsilon_{i,t}$ is the error term.

4. Results

4.1. Main regression results

Table 3 reports the industry distribution and descriptive information of the sample firms. Among the 1395 manufacturing firms, those in the Chemicals and Allied Products industry account for the largest proportion (37.49%), followed by the Instruments and Related Products industry (21.36%) and the Electronic and Other Electrical Equipment industry (19.78%). Table 4 presents the descriptive statistics and correlation matrix for all variables. The multicollinearity test results show that the mean and maximum variance inflation factors (VIFs) are 1.15 and 1.36, respectively. These values are well below the conventional threshold of 10, suggesting that multicollinearity is not a concern.

Table 5 reports the main regression results for the hypothesis tests. Model 1 includes all control variables along with industry and year fixed effects. Model 2 introduces firm-specific climate change exposure as the main independent variable. Models 3 and 4 incorporate the two interaction terms separately. Model 5 presents the full model which includes all variables. We thus focus on Model 5 to interpret the results.

First, the results of Model 5 show that firm-specific climate change exposure has a positive and statistically significant effect on vertical integration ($p < 0.01$), supporting H1. This finding suggests that firm-specific climate change exposure motivates firms to pursue vertical integration. To further interpret the economic significance of our findings, we follow Yu et al. (2019) and re-estimate the regression model using log-transformed measures of both climate change exposure and vertical integration. The results show that firm-specific climate change exposure remains positively and significantly associated with vertical

Table 3
Sample descriptions.

Panel A: Descriptive Statistics					
	Unit	Mean	SD	Min	Max
Total Assets	Million US$	5895.966	23974.414	0.535	375319.000
Sales	Million US$	4165.295	18711.177	−0.294	433526.000
Cost of Goods Sold	Million US$	2559.275	14025.258	0.000	346775.000
Inventories	Million US$	467.773	2161.576	0.000	81715.000
Research and Development Expense	Million US$	255.925	1014.982	0.000	22581.000

Panel B: Industry Distribution			
Two-digit SIC Code	Industry Name	Number of Firms	Percentage
20	Food and Kindred Products	14	1.00
21	Tobacco Products	6	0.43
22	Textile Mill Products	2	0.14
24	Lumber and Wood Products	2	0.14
25	Furniture and Fixtures	7	0.50
26	Paper and Allied Products	7	0.50
27	Printing, Publishing	3	0.22
28	Chemicals and Allied Products	523	37.49
29	Petroleum and Coal Products	5	0.36
30	Rubber and Miscellaneous Plastics Products	13	0.93
32	Stone, Clay, Glass, and Concrete Products	3	0.22
33	Primary Metal Industries	10	0.72
34	Fabricated Metal Products	9	0.65
35	Industrial Machinery and Equipment	133	9.53
36	Electronic and Other Electrical Equipment	276	19.78
37	Transportation Equipment	68	4.87
38	Instruments and Related Products	298	21.36
39	Miscellaneous Manufacturing Industries	16	1.15

integration ($b = 0.25$, $p < 0.01$). This suggests that a 1% increase in firm-specific climate change exposure is associated with a 0.25% increase in vertical integration.

Second, the interaction between firm-specific climate change exposure and geographic diversity is also positive and statistically significant ($p < 0.01$), confirming H2. This result indicates that geographic diversity strengthens the effect of firm-specific climate change exposure on vertical integration. Third, the interaction between climate change exposure and financial stability is also positive and statistically significant ($p < 0.01$), supporting H3.

Overall, these results suggest that firm-specific climate change exposure promotes vertical integration. This effect becomes stronger in firms with greater geographic diversity and higher financial stability.

4.2. Robustness checks

We conduct several robustness tests to further examine our main results. The results are reported in Table 6. First, we re-estimate our regression model using two-way fixed effects with robust standard errors. The results, reported in Model 1 of Table 6, remain consistent with our main findings. Second, we adopt alternative measures of moderators. Specifically, we measure geographic diversity as the number of geographic segments and financial stability as the standard deviation of return on assets over the past seven years (with the sign reversed). The results, reported in Model 2 of Table 6, are again consistent with our main findings.

Third, to address potential endogeneity concerns, we employ a two-stage instrumental variable regression using the greenhouse gas (GHG) impact ratio as the instrument. To construct this variable, we collect data on GHG impact measures from Trucost. This variable is defined as a firm's GHG emission costs (including both direct and indirect costs) relative to its revenue (Bressan, 2025). A valid instrumental variable must fulfill two key requirements: the relevance condition and the exclusion restriction, both of which are satisfied by our instrument.

Regarding the relevance condition, the GHG Impact Ratio reflects a firm's underlying carbon intensity. Firms with a higher ratio are more exposed to carbon-related regulations, carbon pricing, and the broader transition to a low-carbon economy. As a result, these firms tend to face greater scrutiny and discussion around climate-related issues in the market. This provides a strong basis for the relevance condition, as the GHG Impact Ratio is closely correlated with firm-specific climate change exposure.

Turning to the exclusion restriction, there are two main concerns that may violate this condition: first, that the GHG Impact Ratio may be jointly determined with firms' governance structure, and second, that vertical integration may itself influence the GHG Impact Ratio. In our setting, the GHG Impact Ratio reflects the emissions intensity of a firm's production process, which is determined by factors such as energy sources, input composition, and production technologies. These features are typically embedded in firms' fixed production systems and require substantial time and investment to change. As a result, the GHG Impact Ratio does not respond quickly to changes in firms' organizational

Table 4
Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) Vertical Integration	1.000								
(2) Firm-Specific Climate Change Exposure	0.278***	1.000							
(3) Firm Size	0.274***	0.016	1.000						
(4) Return on Assets	0.199***	0.043***	0.408***	1.000					
(5) Leverage	0.001	−0.047***	0.146***	−0.107***	1.000				
(6) Quick Ratio	−0.224***	−0.061***	−0.243***	−0.072***	−0.198***	1.000			
(7) Process Sophistication	−0.103***	−0.030***	−0.111***	−0.214***	0.019*	0.207***	1.000		
(8) Financial Stability	0.099***	0.038***	0.181***	0.191***	0.004	−0.113***	−0.145***	1.000	
(9) Geographic Diversity	0.068***	0.010	0.061***	0.059***	0.038***	−0.078***	−0.035***	0.028***	1.000
Mean	1.033	0.001	6.378	−0.068	0.212	3.280	0.090	−0.165	0.028
Standard Deviation	1.061	0.002	2.101	0.470	0.277	3.659	0.319	0.786	0.126

Notes: *$p < 0.10$, **$p < 0.05$, and ***$p < 0.01$(two-tailed tests).

Table 5
Regression results.

	Dependent Variable: Vertical Integration				
	Model 1	Model 2	Model 3	Model 4	Model 5
Firm-Specific Climate Change Exposure		25.574***(6.131)	22.678***(5.336)	31.452***(7.145)	28.484***(6.342)
Firm-Specific Climate Change Exposure × Geographic Diversity			93.596***(3.499)		88.030***(3.289)
Firm-Specific Climate Change Exposure × Financial Stability				63.923***(4.150)	61.271***(3.974)
Firm Size	0.031***(6.985)	0.032***(7.296)	0.032***(7.204)	0.031***(7.054)	0.031***(6.978)
Return on Assets	0.052***(2.879)	0.050***(2.796)	0.051***(2.848)	0.050***(2.791)	0.051***(2.840)
Leverage	0.024(0.858)	0.026(0.936)	0.025(0.912)	0.027(0.971)	0.026(0.946)
Quick Ratio	−0.006***(-2.598)	−0.006**(-2.525)	−0.006**(-2.549)	−0.006***(-2.581)	−0.006***(-2.602)
Process Sophistication	0.008(1.286)	0.006(1.047)	0.006(1.084)	0.006(1.041)	0.006(1.076)
Financial Stability	0.007(0.739)	0.006(0.656)	0.006(0.665)	−0.012(-1.210)	−0.012(-1.128)
Geographic Diversity	−0.071(-1.138)	−0.061(-0.981)	−0.157**(-2.303)	−0.062(-0.991)	−0.152**(-2.229)
Constant	0.882***(21.736)	0.843***(20.575)	0.849***(20.723)	0.847***(20.684)	0.853***(20.819)
Industry-Fixed Effect	YES	YES	YES	YES	YES
Year-Fixed Effect	YES	YES	YES	YES	YES
Observations	9655	9655	9655	9655	9655
R-squared	0.572	0.573	0.574	0.574	0.574
F-value	15.756	18.539	17.859	18.421	17.677

Notes: *$p < 0.10$, **$p < 0.05$, and ***$p < 0.01$(two-tailed tests). Unstandardized coefficients are reported, with *t*-statistics presented in parentheses.

structure. In addition, while vertical integration may affect how production activities are organized across firm boundaries, it does not immediately alter the underlying technologies or input choices that drive emissions intensity. Therefore, variation in the GHG Impact Ratio is unlikely to be driven by firms' vertical integration decisions.

We report the results from the instrumental variable approach in Model 3 of Table 6. First, the Anderson canonical correlation LM statistic is statistically significant ($p < 0.01$), allowing us to reject the null hypothesis that the model is underidentified. Second, the Cragg–Donald Wald *F*-statistic is 17.449, which exceeds the 10% maximal critical value of 16.38 from the Stock–Yogo weak identification test, suggesting that the instrument is not weak (Stock and Yogo, 2002). In addition, the first-stage results in Model 3 show a positive and significant relationship ($p < 0.01$) between the instrumental variable and the endogenous explanatory variable, supporting the relevance condition. The second-stage results indicate that the coefficient on firm-specific climate change exposure remains positive and statistically significant ($p<0.01$), which is consistent with our baseline findings.

Furthermore, we acknowledge that the instrumental variable approach may not fully eliminate all endogeneity concerns. To address this issue, we conduct a placebo test by randomly assigning climate change exposure to all sample firms. We repeat this randomization process 500 times and re-estimate the baseline model for each iteration. As illustrated in Fig. 2, the distribution of the estimated coefficients from these random assignments is centered around zero and follows an approximately normal pattern, suggesting that our results are unlikely to be driven by unobserved confounding factors.

Lastly, we estimate a System Generalized Method of Moments (GMM) model to further address unobserved heterogeneity and reverse causality. As shown in Table 7, we include the lagged dependent variable (L.Vertical Integration) and treat climate change exposure as endogenous. Following Liang et al. (2024), we use all available lagged values starting from *t*–2 as instruments in the first stage and estimate the system GMM model accordingly. To ensure the robustness of our system GMM estimates, we also restrict the maximum lag length of the instruments to *t*–4 and *t*–5 in Models 2 and 3 of Table 7, respectively. Across all specifications, the coefficients on firm-specific climate change exposure remain positive and statistically significant. Moreover, the AR (2) and Hansen test results are consistently insignificant ($p > 0.1$), indicating no evidence of second-order serial correlation and supporting the validity of the instruments used in the system GMM. Overall, the results from the system GMM model are consistent with our baseline findings.

5. Discussions and implications

5.1. Implications for research

Drawing on the TCE lens, our study contributes to the growing literature at the intersection of climate change, operations management, and corporate strategy. First, our study shows that firm-specific climate change exposure, as perceived by market participants, shapes firms' boundary decisions. In particular, we demonstrate that market-based evaluations of climate change impacts lead firms to internalize inter-organizational relationships through vertical integration. By doing so, our study shifts the focus from exogenous climate shocks to perception-based signals as a key driver of firms' boundary choices.

Second, while prior research has primarily focused on intra-organizational responses to climate change, such as green innovation, green governance, and green transformation (Chen et al., 2024; Fatica and Panzica, 2021; Lerman et al., 2022; Liu et al., 2024; Su and Moaniba, 2017), it has largely overlooked how climate change influences firms' organizational boundaries. In this regard, we further extend the literature by examining how firms restructure their boundaries through the internalization of inter-organizational relationships in response to external environmental uncertainty (Jacobides, 2008; Ketokivi and Mahoney, 2020).

Furthermore, our study contributes to the literature on global operations by considering the moderating role of geographic diversity. While prior studies often view geographic diversification as a risk mitigation strategy (Fan et al., 2022; Nippa et al., 2021), we show that under climate change exposure it can instead amplify transaction costs. That is, geographic dispersion exposes firms to heterogeneous regulatory environments and increases coordination complexity across regions. These conditions make contracts harder to design and enforce, raising governance costs in market exchanges. As a result, the benefits of diversification may be offset by higher transaction costs, leading firms to rely more on internal coordination through vertical integration. In this way, we offer a more nuanced view of how geographic diversification affects firms' organizational decisions.

Finally, we incorporate financial stability as a key contingency shaping firms' boundary decisions. Under climate change exposure, firms face higher transaction costs in market exchanges. While vertical integration can mitigate these costs, it also entails substantial internal governance costs and long-term investment. Firms with greater financial stability are better able to absorb these costs and sustain internal coordination, making them more likely to internalize transactions. In this way, our findings show that firms' internalization decisions depend not only on transaction costs but also on their capacity to bear the costs of internal governance.

Table 6
Robustness checks.

	Model 1	Model 2	Model 3	
	Robust standard error estimation	Alternative measures of moderators	First-stage	Second-stage
	Vertical Integration	Vertical Integration	Climate Change Exposure ($\times 10^2$)	Vertical Integration
Firm-Specific Climate Change Exposure	28.4839*** (4.5305)	24.3846*** (4.2125)		580.3340*** (3.4068)
Firm-Specific Climate Change Exposure × Geographic Diversity	88.0298*** (2.7099)	6.6997** (2.3410)		
Firm-Specific Climate Change Exposure × Financial Stability	61.2705** (2.4683)	64.2243*** (4.8952)		
Instrumental Variable: GHG Impact Ratio			0.0175*** (4.1772)	
Firm Size	0.0310*** (7.1227)	0.0304*** (6.8586)	−0.0068*** (-3.8340)	0.0483*** (2.8413)
Return on Assets	0.0508*** (2.7134)	0.0485*** (2.7168)	0.0168 (1.3680)	0.0213 (0.2304)
Leverage	0.0264 (1.4161)	0.0274 (0.9826)	0.0012 (0.1171)	0.0311 (0.4398)
Quick Ratio	−0.0058*** (-4.7293)	−0.0057** (-2.5608)	0.0004 (0.4971)	−0.0062 (-1.0681)
Process Sophistication	0.0064* (1.6454)	0.0068 (1.1567)	0.0058*** (2.6932)	−0.0205 (-1.1201)
Financial Stability	−0.0116* (-1.7301)	−0.0061 (-1.1135)	0.0060 (1.0831)	−0.0218 (-0.5312)
Geographic Diversity	−0.1517** (-2.0400)	−0.0142 (−1.5380)	0.0458** (2.0619)	−0.3608** (-2.0608)
Constant	0.8529*** (23.0574)	0.8703*** (20.5369)	0.1476*** (8.3327)	1.0926*** (3.5720)
Industry-Fixed Effect	Yes	Yes	Yes	Yes
Year-Fixed Effect	Yes	Yes	Yes	Yes
Observations	9655	9655	4953	4953
R-squared	0.574	0.574	0.388	0.056
F-value	18.202	17.83	6.471	17.449

Notes: *$p < 0.10$, **$p < 0.05$, and ***$p < 0.01$(two-tailed tests). Unstandardized coefficients are reported, with *t*-statistics presented in parentheses.

5.2. Implications for managers

Our study offers several practical implications for managers seeking to navigate climate change related uncertainties. First, climate change introduces not only environmental challenges, but also substantial operational, strategic, and supply chain uncertainties. Managers should recognize that climate change exposure affects firm decision-making beyond traditional sustainability metrics, such as carbon emissions or environmental rankings. Our findings highlight that climate-related uncertainty increases transaction costs in market exchanges, which may prompt firms to reconsider their value chain structure and move toward vertical integration. Rather than treating integration as a purely cost-driven decision, managers can use it as a mechanism to secure supply and enforce sustainability standards under conditions of heightened uncertainty.

Second, our results indicate that the impact of climate change exposure is more pronounced for firms with high geographic diversity. Operating across multiple regions exposes firms to heterogeneous regulations and uneven climate risks, which amplify coordination complexity and make contractual arrangements more difficult to manage. As a result, managers in geographically diversified firms should be particularly attentive to these challenges and consider vertical integration as a tool to improve coordination and reduce exposure to fragmented external environments.

In addition, our findings highlight that the effectiveness of vertical integration depends on firms' financial stability. While vertical integration can mitigate transaction costs, it also increases substantial internal governance costs and requires long-term investment. Managers should therefore carefully assess whether their organizations have sufficient financial resources and strategic commitment to support such restructuring. Firms with stronger financial stability are better positioned to internalize activities, whereas financially constrained firms may need to rely on alternative strategies despite facing similar external

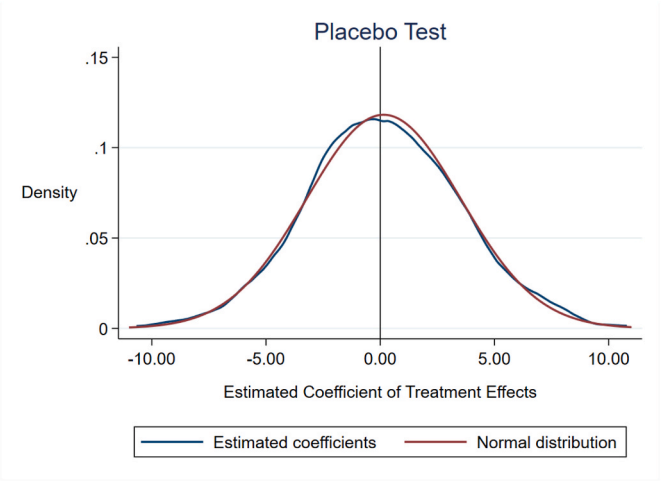


Fig. 2. Placebo test.

Table 7
System GMM results.

	Model 1 (Lag *t*-2)	Model 2 (Lag *t*-2 to *t*-4)	Model 3 (Lag *t*-2 to *t*-5)
L.Vertical Integration	0.772*** (15.780)	0.804*** (16.166)	0.800*** (17.496)
Firm-Specific Climate Change Exposure	18.914*** (3.035)	16.360** (2.237)	18.087** (2.511)
Firm Size	0.021*** (3.348)	0.021*** (2.995)	0.021*** (3.288)
Return on Assets	0.035 (1.621)	0.029 (1.440)	0.029 (1.444)
Leverage	−0.025 (-1.362)	−0.027 (-1.370)	−0.025 (-1.329)
Quick Ratio	−0.007*** (-3.263)	−0.006*** (-2.712)	−0.006*** (-2.904)
Process Sophistication	−0.006* (-1.712)	−0.006* (-1.833)	−0.007* (-1.952)
Constant	0.065 (1.639)	0.039 (1.050)	0.035 (0.972)
Industry-Fixed Effect	Yes	Yes	Yes
Year-Fixed Effect	Yes	Yes	Yes
Arellano-bond test for AR (1) (*p*-value)	0.000	0.000	0.000
Arellano-bond test for AR (2) (*p*-value)	0.940	0.965	0.961
Hansen test (*p*-value)	0.214	0.133	0.225
Observations	8051	8051	8051

Notes: *$p < 0.10$, **$p < 0.05$, and ***$p < 0.01$(two-tailed tests). Unstandardized coefficients are reported, with *t*-statistics presented in parentheses.

pressures.

Furthermore, our study provides guidance for managers evaluating vertical integration opportunities under climate-related uncertainty. Such decisions should not be based solely on the presence of climate-related risks. Instead, managers should assess: (1) which supply chain activities are strategically important to the firm, and (2) whether internalizing these activities creates greater value than relying on external suppliers. For example, Tesla's approach to battery material sourcing illustrates how firms may identify strategically important supply chain activities for potential integration (Harryson and Lorange, 2024; Serohi, 2022). Battery materials, such as lithium and nickel, are critical inputs for electric vehicle production and directly influence Tesla's market position. Rather than integrating all supply chain activities, Tesla has focused on gaining greater control over upstream activities related to battery materials that are strategically important and exposed to supply uncertainty. This example highlights that managers should first identify critical supply chain activities before determining whether vertical integration represents an appropriate governance choice.

Lastly, managers should not assume that vertical integration is always the optimal response to climate-related risk and uncertainty. This is because vertical integration often involves substantial investment, reduces flexibility, and creates additional internal coordination and governance demands. Therefore, before pursuing vertical integration, firms should carefully evaluate whether such a strategy aligns with their strategic objectives (e.g., desired level of supply chain control and long-term competitive priorities) and whether they possess sufficient organizational capabilities and resources to support such implementation. Firms that prioritize greater control over critical supply chain activities and possess stronger financial and organizational resources may be better positioned to benefit from vertical integration. In contrast, firms whose strategic priorities emphasize flexibility, asset-light business models, or rapid adaptation may need to consider alternative governance arrangements.

6. Conclusion and limitations

By employing a two-way fixed effects regression on a sample of U.S. manufacturing firms, our study shows that firms are more likely to pursue vertical integration in response to increased firm-specific climate change exposure. Moreover, this relationship is contingent on firms' operational and financial conditions. In particular, firms with greater geographic dispersion and stronger financial stability are more likely to rely on vertical integration as a governance response to climate-related exposure.

While our study offers important theoretical and managerial implications, it is not without limitations, which point to promising avenues for future research. First, although we control for industry fixed effects, vertical integration decisions may still be influenced by industry-specific characteristics, such as value chain complexity, technological intensity, and regulatory environments. Future research could build on this by examining how industry characteristics interact with climate change exposure to influence firms' boundary decisions.

Second, our study adopts a TCE perspective to explain how firm-specific climate change exposure leads firms to pursue vertical integration. However, our quantitative approach may not fully capture the underlying mechanisms driving this relationship. Future research could complement our findings by employing qualitative methods, such as case studies or interviews, to provide deeper insights into the decision-making processes underlying firms' boundary choices.

Third, the measure of firm-specific climate change exposure combines both risk and opportunity components. While focusing solely on the risk component may align more directly with an uncertainty-based perspective, such data are not available in the Sautner et al. (2023a) dataset. Future research could address this limitation by examining the risk component separately when relevant data become available. In addition, we also acknowledge the limitations of the proxy used for vertical integration. Our measure is based on firms' reported activity scopes across vertically related industries. Although this approach is widely used in prior research, it does not directly observe ownership activities. Future research thus could employ more direct measures to further validate our findings.

Moreover, such measurement for climate change exposure raises the possibility that the relationship between market-perceived climate change exposure and vertical integration involves multiple underlying mechanisms. For example, greater external attention to climate-related risks may amplify stakeholder pressure, thus encouraging firms to adopt vertical integration as a strategic response. Therefore, future studies could adopt primary data collection approaches, such as surveys and interviews, to further examine these mechanisms and better understand how market-perceived climate change exposure influences firms' vertical integration choices.

Fourth, our measure of geographic diversity has several limitations. Specifically, segment disclosures are based on SEC reporting requirements, which require firms to report only segments that exceed certain materiality thresholds (typically around 10% of assets, revenue, or profits). As a result, smaller geographic segments may not be fully captured in our measure. This may lead to a conservative estimate of geographic diversity, particularly for firms with highly fragmented operations. Future research could address this limitation by using more granular data or alternative measures that capture smaller or less material geographic segments, where such data are available.

Lastly, as our study focuses on U.S. manufacturing firms, the generalizability of our findings may be limited. Institutional and regulatory environments vary substantially across countries, particularly between developed and emerging economies. For instance, firms in emerging markets may face weaker regulatory enforcement, different stakeholder pressures, and more constrained access to green technologies and financing. Future research could therefore explore how institutional environments and industry characteristics jointly shape firms' responses to climate-related uncertainty.

CRediT authorship contribution statement

Miaomiao Zhang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hugo K.S. Lam:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Conceptualization. **Yangchun Xiong:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Peter K.C. Lee:** Writing – review & editing, Supervision, Resources, Conceptualization. **Andy C.L. Yeung:** Writing – review & editing, Supervision, Resources, Conceptualization. **T.C.E. Cheng:** Writing – review & editing, Supervision, Resources, Conceptualization.

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