



From disclosure to decision: how climate risk shapes firms' human capital strategies in China

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Received: 30 June 2025 / Accepted: 24 August 2025 / Published online: 4 October 2025
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Abstract

Amid the global green transition, how climate risk influences corporate resource allocation especially human capital investment has become a key concern. Using panel data on Chinese A-share Listed firms from 2008 to 2022, this study applies a two-way fixed effects model to examine how climate risk affects corporate human capital upgrading. Results show that climate risk significantly constrains firms' workforce development, particularly among non-SOEs, financially constrained firms, and those in regions with low talent endowment or high physical climate exposure. Mechanism tests reveal that climate risk inhibits strategic investment in human capital by increasing perceived uncertainty, intensifying managerial short-termism, and tightening financial constraints. This study significantly contributes to the micro-level literature on climate risk and corporate capability building, thereby extending the theoretical understanding of how environmental uncertainty shapes long-term capability development, and offers practical guidance for firms and policymakers seeking to enhance workforce resilience in volatile environmental conditions.

Keywords Climate risk · Human capital upgrading · Perceived uncertainty · Managerial short-termism · Financial constraints

1 Introduction

Human capital plays a pivotal role in driving sustainable economic growth, serving as the foundation for firms' technological advancement, green transition, and long-term

strategic development (Cui and Diwu 2024; Koppensteiner and Menezes 2021; Li et al. 2025a, b). Amid the ongoing wave of technological revolution and industrial restructuring, firms' reliance on a highly educated, environmentally competent workforce has become increasingly salient (Ma et al. 2024). Accordingly, the upgrading of human capital has evolved into a core objective of national development strategies and industrial policy frameworks. According to the International Labour Organization (ILO), an estimated 120 million jobs worldwide will undergo structural transformation over the next decade due to green transition pressures (Wen et al. 2025). A firm's ability to invest in and retain high-skilled talent will thus largely determine its resilience and competitiveness in this evolving landscape.

In China, national strategies such as "Skilled China" and "Education Power" have continuously emphasized the strategic value of talent in enabling industrial upgrading. However, structural shortages in talent supply remain a pressing issue. As of 2024, China had over 200 million skilled workers, but only around 60 million were classified as high-skilled roughly 30% of the total, significantly lower than the 50% average across developed economies. Existing research further shows that Chinese firms often

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struggle with issues such as inadequate training systems, talent mismatch, and low workforce retention (Heckman 2005; Li 2024). These constraints undermine firms' ability to modernize their workforce and respond to longer-term strategic imperatives. Accordingly, identifying and clarifying the key external factors that influence firms' human capital upgrading is of both theoretical relevance and practical significance for advancing factor modernization and enhancing corporate strategic capacity (Duleep and Regets 1999; Jacobs 2007; Bouché and Modesto 2025).

Among these external factors, climate risk has emerged as a critical but underexplored constraint on corporate human capital strategy (Ma et al. 2025a). According to the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), extreme climate events, such as heatwaves, floods, and droughts, are becoming increasingly frequent and severe, evolving from sporadic disruptions into structural threats (Tong et al. 2025). These events not only destabilize supply chains and infrastructure but also create profound uncertainty in corporate planning (Wu et al. 2025). The Swiss Re Institute projects that if global temperatures rise by more than 2.6 °C by 2050, the world economy may experience annual output losses of 11–14%, equivalent to around USD 23 trillion per year. Some developing economies may suffer output losses exceeding 20% or even 40%. In China, the 2022 heatwave caused significant power shortages, forcing leading firms in Sichuan and Chongqing including CATL and Toyota China to suspend operations. Recent studies also find that extreme temperatures can lead to cuts in training budgets, delays in talent development programs, and a reduction in skilled labor demand (Shayegh et al. 2021; LoPalo 2023).

While a growing body of literature has explored the consequences of climate risk for corporate capital structure, adaptive strategies, and operational performance (Ginglinger and Moreau 2023; Hao et al. 2025; Li 2025), the literature has not yet systematically examined whether and how climate risk reshapes human capital investment behavior at the firm level. In particular, little is known about the mechanisms through which climate-induced uncertainty disrupts strategic labor decisions, or how this relationship varies across firms and regions. Against the backdrop of the global green transition, this research question also holds significant relevance for other emerging economies (Zhang et al. 2025). For instance, countries such as India and Brazil face frequent extreme climate events and policy uncertainty, and their manufacturing firms experience both similarities and context-specific differences compared to China in terms of climate adaptation investment, human capital development, and institutional support¹(Zeng et al. 2025a). China's

distinctive characteristics in industrial scale, regional disparity, and policy orientation make it a representative case for studying the impact of climate risk on human capital upgrading, which not only deepens the understanding of adaptation pathways in emerging economies but also provides valuable lessons for other countries navigating climate-related uncertainty.

To fill this gap, this study explores three central questions. First, does climate risk significantly suppress firms' commitment to upgrading human capital? Second, is this effect mediated through mechanisms such as heightened uncertainty perception, increased managerial short-termism, and intensified financial constraints? Third, are these effects heterogeneous across ownership types, financing capacities, or regional institutional and resource environments?

To answer these questions, we analyze panel data on Chinese A-share Listed firms from 2008 to 2022 and apply a two-way fixed effects model. The findings reveal that climate risk significantly reduces firms' investments in human capital upgrading. This result remains robust after a series of tests, including instrumental variable estimations. Heterogeneity analyses suggest that the adverse effects of climate risk are more pronounced among non-state-owned enterprises, firms facing greater financing constraints, those operating in regions with weaker talent endowments, and those with higher exposure to physical climate risks. Mechanism analyses confirm that climate risk inhibits firms' human capital upgrading through three channels: increasing perceived uncertainty about future environments, reinforcing managerial myopia, and exacerbating financial constraints. These results contribute to a deeper understanding of the behavioral foundations of corporate adaptation under environmental uncertainty.

The remainder of this paper is organised as follows. Section 2 reviews the related literature, identifies the research gap, and outlines the main contributions of this study. Section 3 develops the theoretical framework regarding how climate risk influences corporate human capital upgrading and proposes the corresponding research hypotheses. Section 4 describes the empirical strategy, including model specification and sample construction. Section 5 presents the baseline regression results, robustness checks, and strategies for addressing potential endogeneity. Section 6 conducts the mechanism and heterogeneity analyses. Section 7 concludes with a summary of key findings and discusses the policy implications.

¹ Financial Times, Parag Khanna, 2024. India is overlooking the climate drag on its economic growth. <https://www.ft.com/content/927a>

4c8b-db4c-4a46-af68-71c5a03452ab; IMF eLIBRARY, Chen et al., 2024. Changing Climate in Brazil: Key Vulnerabilities and Opportunities. DOI: <https://doi.org/10.5089/9798400289361.001>.

2 Literature review and innovation points

This study is closely related to a growing body of literature examining the economic consequences of climate risk and its implications for corporate behavior. With the increasing frequency of extreme weather events and the advancing dual-carbon strategy in recent years, climate risk has become widely recognized as a systemic external shock, drawing considerable scholarly attention (Liu et al. 2025). Existing research has explored the disruptive effects of climate risk at both macro and micro levels. At the macro level, studies have shown that climate policy uncertainty significantly increases urban climate vulnerability (Ahmed et al. 2023), while also exerting a negative influence on urban energy efficiency and low-carbon transitions (Zhou et al. 2025; Han et al. 2025). At the micro level, climate risk contributes to heightened uncertainty in both policy and market expectations, leading firms to adopt more conservative strategies and enhanced risk management behaviors. For instance, exposure to climate shocks has prompted firms to restructure supply chains by diversifying upstream and downstream relationships and reducing network concentration to mitigate operational risk (Su et al. 2025). Moreover, climate risk can weaken internal cash flows, raise the cost of external financing, increase the probability of default, and widen corporate credit spreads, ultimately reducing firm value (He et al. 2025; Peng et al. 2025). Rising levels of climate exposure have also intensified public and managerial perceptions of environmental threats, spurring stronger adaptive responses (Li 2025). Empirical research has further demonstrated that extreme heat reduces firms' electricity efficiency and operational performance (Hao et al. 2025), while in certain contexts, it may enhance intra-organizational cooperation particularly among employees with lower productivity or higher environmental awareness (Gong et al. 2025).

Although substantial progress has been made in understanding how climate risk affects corporate finance, investment, operations, and ESG performance, relatively little is known about whether and how climate risk systematically inhibits firms' human capital upgrading through behavioral micro-mechanisms. In particular, there is a lack of empirical evidence on how climate risk may reshape firms' long-term factor allocation strategies by constraining their commitment to human capital upgrading. This study also contributes to the literature examining the determinants of corporate human capital upgrading. As a foundational asset that supports green transformation, fosters technological advancement, and enhances organizational resilience, human capital has increasingly become a focal point in the fields of organizational behavior and strategic management. A growing body of research emphasizes that firms' investment in

human capital is shaped by both internal incentive mechanisms and external institutional environments.

From an internal perspective, empirical evidence suggests that ESG disclosure quality, major customer announcement events, corporate contributions to social security, and even incidents of student violence can significantly affect firms' human resource allocation decisions (Koppensteiner and Menezes 2021; Aobdia et al. 2025; Ni 2025; Xiang and Huang 2025). From an external institutional perspective, macro-level policies, regional shocks, and broader societal changes also impose substantial constraints on corporate human capital strategies. For instance, studies have shown that initiatives such as China's intelligent manufacturing programs (Li et al. 2025a, b), exposure to natural disasters (Oppen et al. 2023), early-life flood experience (Huang and Dong 2025), trade liberalization (Fu 2024), the expansion of social security programs (Deshpande and Dizon-Ross 2023), and changes in migration policy (Adda et al. 2022) all exert significant influence on firms' willingness and capacity to invest in talent cultivation, skill upgrading, and structural optimization. Notably, rising uncertainty surrounding climate-related policies has been found to encourage more flexible employment strategies such as labor outsourcing, with such behavioral adjustments being particularly pronounced among privately-owned firms (Li et al. 2025a, b).

While these studies provide important insights into the economic consequences of climate risk and the institutional determinants of corporate human capital upgrading, there remains a lack of a systematic theoretical framework and empirical evidence on the behavioral mechanisms through which climate risk may suppress strategic investment in human capital. This study seeks to address this critical gap by uncovering how external shocks such as climate risk interact with firms' internal capabilities and long-term resource commitments. From a theoretical perspective, climate risk, as a systemic external shock, can influence firms' long-term capability-building decisions by disrupting their strategic expectations and resource constraints. According to the resource-based view, a firm's sustained competitive advantage depends on core resources that are rare, inimitable, and value-generating, among which high-quality human capital is critical for achieving technological advancement and organisational resilience (Barney 1991). Human capital theory posits that investments in human capital are long-term in nature and highly uncertain, making them more susceptible to cutbacks when external environmental turbulence intensifies (Gervais et al. 2008). The theory of environmental uncertainty further emphasises that when external shocks reduce the predictability of future returns, managers tend to contract high-risk, long-horizon strategic investments (FeldmanHall and Shenhav 2019). Given that climate risk manifests not only as physical shocks but

also through policy uncertainty and market responses that shape the business environment (Sautner et al. 2023), it can be theoretically inferred that it has a suppressive effect on corporate human capital upgrading. Therefore, adopting climate risk as the core explanatory variable and human capital upgrading as the key outcome variable is both theoretically grounded and instrumental in revealing the mechanisms through which external uncertainty affects firms' factor allocation structures.

This study offers several key contributions to the existing literature. First, it broadens the analytical scope by revealing how climate risk affects internal factor allocation, particularly human capital upgrading. While prior research has emphasized green innovation, firm performance, and ESG outcomes (Li et al. 2024; Ma and Appolloni 2025; Ren et al. 2022; Tian et al. 2024), limited attention has been paid to the behavioral channels through which climate risk disrupts firms' strategic expectations and talent development. Using firm-level data from Chinese A-share listed companies, this study conceptualizes climate risk as a form of systemic uncertainty shock and empirically demonstrates its constraining effect on firms' human capital strategies amid the green transition.

Second, the study develops a novel framework focused on expectation disruption, identifying three mechanisms: increased perceived uncertainty, reinforced managerial short-termism, and intensified financial constraints. These dimensions jointly shape firms' strategic response to environmental volatility, leading to reduced long-term investment in workforce development.

Third, the analysis reveals heterogeneous effects of climate risk across ownership types, financial capacities, and regional contexts. The inhibitory impact is more severe for non-state-owned enterprises, financially constrained firms, and firms in regions with limited human capital endowment or high physical climate exposure. These findings underscore the importance of context-sensitive policy interventions to mitigate vulnerability and support sustainable talent strategies. Overall, the study offers both theoretical insights and actionable implications for enhancing organizational resilience and human capital investment under climate uncertainty.

3 Theoretical framework and research hypotheses

An increase in climate risk implies a higher probability and intensity of external shocks, which not only heightens operational pressures but also compels management to reprioritize resource allocation at the strategic level (Sautner et al.

2023). Under constraints of limited financial and managerial resources, firms are more likely to channel resources toward climate adaptation, environmental compliance, and operational safety expenditures that are rigid and non-deferrable to safeguard short-term operational stability (Yang and Geng 2025). Such adaptive spending directly absorbs budgets and organisational attention that would otherwise be dedicated to human capital upgrading (Innocenti and Golin 2022). Given the long payback horizon and delayed returns of human capital investment, these budgets are often viewed as compressible under resource strain, making them susceptible to reduction or postponement during periods of heightened climate risk (Ma et al. 2025b). Therefore, higher perceived climate risk will directly suppress firms' human capital upgrading. Based on this, this article proposes hypothesis 1:

Hypothesis 1 *Climate risk has a suppressive effect on firms' human capital upgrading.*

Climate risk, as a systemic source of environmental uncertainty, can reshape firms' strategic expectations and resource allocation beyond direct physical or regulatory disruptions. Human capital upgrading, characterised by long horizons and uncertain returns, is particularly vulnerable. To capture the multi-dimensional nature of this impact, this study proposes a three-channel framework. At the cognitive level, climate risk heightens firms' perceived uncertainty regarding their future operating environment. At the behavioural level, heightened uncertainty can reinforce managerial short-termism, prompting decision-makers to prioritise immediate outcomes over long-term capability development. At the structural level, climate risk can tighten financial constraints, limiting the resources available for strategic workforce investments. Together, these pathways reduce firms' willingness and capacity to undertake long-term human capital upgrading, thereby linking environmental uncertainty to internal capability building through distinct cognitive, behavioural, and structural mechanisms.

3.1 Heightened perception of uncertainty

Climate risk primarily affects firms by disrupting external expectations and amplifying their perceived uncertainty about future operating environments. According to organizational information theory, rising environmental uncertainty increases firms' cognitive biases regarding future returns, regulatory shifts, and market dynamics, thereby encouraging defensive or risk-averse strategies and reducing their commitment to high-risk, long-term investments (Dahlmann and Roehrich 2019; Ying et al. 2025). Given

the persistent, unpredictable, and regionally heterogeneous nature of climate risk, firms often find it difficult to assess the potential impact of extreme weather events, evolving climate regulations, or decarbonization pressures on operational performance (Wu et al. 2024). As a result, they are more likely to adopt “wait-and-see” or conservative strategies, reinforcing risk aversion in strategic decision-making (Hao et al. 2025; He et al. 2025). From a theoretical perspective, decisions related to high-skilled talent acquisition, workforce training systems, and organizational capability upgrading rely heavily on firms' confidence in future environmental stability. Existing studies show that environmental uncertainty weakens firms' willingness to pursue growth-oriented investments (Gong et al. 2025; Li et al. 2024), and undermines their incentives for organizational learning and knowledge accumulation (Enseñado et al. 2025), which in turn threatens long-term competitiveness. Accordingly, under conditions of heightened climate-induced uncertainty, firms are more likely to delay or downscale strategic human capital initiatives. Based on this, this article proposes hypothesis 2:

Hypothesis 2 *Climate risk suppresses firms' human capital upgrading by heightening perceived environmental uncertainty.*

3.2 Reinforcing managerial myopia

In the face of heightened uncertainty induced by climate risk, managerial behavioral responses constitute a critical channel through which firms adjust their strategic priorities. Managerial myopia, a well-documented decision-making bias, refers to the tendency of corporate executives to prioritize short-term, quantifiable performance metrics at the expense of long-term value creation and sustainable capability development (Lavery 1996; Zeng et al. 2025b). According to the theory of managerial short-termism, external uncertainty amplifies managers' preference for immediate returns, prompting a departure from long-term, value-driven strategic orientations. Prior research has shown that managerial myopia significantly suppresses firm-level expenditures in RandD, environmental investment, and organizational learning (Holden and Lundstrum 2009; Zhu et al. 2025). As a salient form of systemic uncertainty, climate risk may exacerbate managerial short-termism in multiple ways (Stein 1989). On the one hand, ambiguity surrounding climate regulations such as carbon pricing mechanisms and green compliance requirements makes it difficult for managers to evaluate the pace and cost of policy implementation, reinforcing risk-averse tendencies. On the other hand, intensifying scrutiny

from investors on firms' ESG performance, combined with conditionalities attached to green financing and growing reputational concerns, places dual pressure on managers to balance short-term financial stability with environmental compliance. Under such circumstances, managers are more likely to reallocate firm resources away from long-term, non-obligatory investments and toward liquidity preservation, operational efficiency, and near-term reporting metrics. Human capital upgrading particularly in areas like workforce training, skill enhancement, and organizational renewal tends to be categorized as “compressible expenditure,” and thus is often postponed or scaled back during periods of strategic contraction. Based on this, this article proposes hypothesis 3:

Hypothesis 3 *Climate risk suppresses firms' human capital upgrading by reinforcing managerial short-termism.*

3.3 Intensifying financial constraints

Climate risk may also inhibit firms' strategic investment in human capital by exacerbating financial constraints. Prior studies have consistently identified financing constraints as a major barrier to long-term corporate investment, especially in areas with delayed returns such as human capital upgrading, RandD, and green transformation (Mills et al. 1995; Li et al. 2021). The tightening of financial conditions under climate risk manifests in two primary forms. First, extreme weather and climate-related events disrupt firms' operational stability and erode cash flow and asset quality, thereby elevating default risks and reducing borrowing capacity (Naseer et al. 2025; He et al. 2025). Second, under emerging green finance regulatory frameworks, financial institutions increasingly incorporate firms' environmental performance and climate exposure into their credit evaluations. As a result, carbon-intensive firms face higher financing thresholds and rising capital costs (Huang et al. 2022). Empirical research based on data from 8,265 firms across 25 transition economies further shows that access to finance particularly constraints on bank lending significantly reduces corporate spending on on-the-job training and other forms of human capital investment (Popov 2014). Complementary evidence also suggests that firms are more inclined to engage in CSR-related activities, including employee welfare, during periods of relaxed financing conditions (Yousaf et al. 2025). In the context of heightened climate risk and restricted credit access, investments in training, skill enhancement, and organizational capacity building which are often regarded as flexible and non-essential are typically among the first to be delayed or cut. Based on this, this article proposes hypothesis 4:

Hypothesis 4 *Climate risk suppresses firms' human capital upgrading by intensifying financial constraints.*

4 Research design

4.1 Model specification

To empirically test the hypotheses proposed above, we follow the methodological approach adopted in prior studies (Song et al. 2024), and construct the following baseline regression model to examine the impact of climate risk on firms' human capital upgrading:

$$Upgrade_{it} = \alpha + \beta_1 Risk + \lambda X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

In this specification, the subscripts i and t denote firm and year, respectively. The dependent variable Upgrade captures the degree of human capital upgrading, measured by the educational attainment of employees within each firm. Risk represents the firm-specific climate risk exposure. X_{it} denotes a vector of control variables, and ε is the error term. To address potential unobserved firm-specific heterogeneity and time-varying macroeconomic shocks, we include firm and year fixed effects. Standard errors are clustered at the firm level to account for potential serial correlation and heteroskedasticity in the error terms.

4.2 Sample selection and data sources

To ensure data availability and consistency, this study uses panel data of A-share Listed firms in Shanghai and Shenzhen stock exchanges from 2008 to 2022. Firm-level data are obtained from the China Stock Market and Accounting Research (CSMAR) database. Following established practices in the literature (Li et al. 2025a, b; Su et al. 2025), we exclude firms in the financial sector, firms with special treatment (ST, *ST, and PT classifications), and firms with missing values in key variables. To mitigate the influence of outliers, all continuous variables are winsorized at the 1% level. After this screening process, the final dataset comprises 29,322 firm-year observations.

4.3 Variable description

4.3.1 Dependent variable

The dependent variable in this study is the level of human capital upgrading within the firm (Upgrade). Consistent with human capital theory, education and training are core investments that raise workforce productivity, so education-based and occupation-based indicators are widely used to

capture upgrading in the skills structure (Goldin 2019). Following prior literature (Li et al. 2025b; Ni 2025), we measure human capital upgrading based on employees' educational attainment. Specifically, Upgrade is defined as the proportion of employees with a college degree or above in the total workforce of a firm. As a robustness check, we adopt an alternative measure based on job function, defining human capital upgrading as the proportion of technical personnel in the total number of employees, which aligns with occupation-based proxies commonly recommended in international practice for assessing workforce capabilities².

4.3.2 Key explanatory variable

The key explanatory variable Climate Risk (Risk), captures the level of climate risk faced by the firm. A disclosure-based, text-analysed index is suitable for reflecting managerial perceptions of climate exposure, since institutional investors treat climate risks as financially material for portfolio firms and rely on disclosed information in decision-making (Krueger et al. 2020). Recent finance research further developed machine-learning text methods to quantify firm-level climate exposure from corporate reports and showed that these measures map to physical and regulatory dimensions and are informative for markets (Sautner et al. 2023). Global reporting guidance has also formalised disclosure of climate-related risks in mainstream filings across governance, strategy, risk management and metrics, which legitimises an annual-report-based approach (TCFD, Task Force on Climate-related Financial Disclosures)³.

Following established methodologies in the literature (Sautner et al. 2023; Su et al. 2025), we quantify corporate climate risk by computing the frequency of "climate risk"-related terms in annual reports of A-share listed firms in China, using textual analysis and machine learning techniques. Specifically, we construct the firm-level climate risk index through the following steps. First, we collect annual reports of all A-share listed firms during the sample period from CNINFO (The website for information disclosure of Chinese listed companies, <https://www.cninfo.com.cn/>). Second, drawing on policy documents, data released by the National Meteorological Science Data Center, and the China Meteorological Disaster Yearbook, we compile a dictionary of seed terms related to "climate risk." Third, using machine learning models as employed in prior research (Li et al. 2024), we expand the dictionary by identifying semantically similar terms in the text corpus. Fourth, for

² OECD (2019), OECD Skills Strategy 2019: Skills to Shape a Better Future, OECD Publishing, Paris, <https://doi.org/10.1787/9789264313835-en>.

³ TCFD. (2021), Status Report, https://assets.bbhub.io/company/sites/60/2022/03/GPP_TCFD_Status_Report_2021_Book_v17.pdf.

each firm-year observation, we calculate the proportion of climate risk-related terms relative to the total word count in the annual report, which serves as the climate risk index. A higher value of this index indicates greater perceived exposure to climate-related risks. The coefficient β_1 represents the effect of climate risk on human capital upgrading. A significantly negative β_1 would support Hypothesis 1, suggesting that heightened climate risk significantly inhibits firms' strategic investment in upgrading human capital.

4.3.3 Control variables

Following prior empirical studies (He et al. 2025; Li et al. 2025a, b; Su et al. 2025), we include a set of firm-level control variables that may influence human capital upgrading. To mitigate potential heteroskedasticity and serial correlation in the residuals, we use heteroskedasticity-robust

Table 1 Variable definition

Variables	Definition
Upgrade	Human Capital Upgrading: Measured by the proportion of employees with a college degree or above relative to total employees, reflecting the firm's investment in higher-educated labor.
Risk	Climate Risk: Measured as the proportion of climate risk-related terms, identified through a domain-specific dictionary and expanded using machine learning, in the annual reports of A-share listed firms.
Size	Firm Size: Natural logarithm of total assets at the end of the fiscal year.
Lev	Leverage Ratio: Total liabilities divided by total assets.
ROA	Return on Assets: Net profit divided by total assets.
Cash	Operating Cash Flow: Net cash flow from operating activities divided by total assets.
Age	Firm Age: Natural logarithm of the number of years since the firm's listing.
Board	Board Size: Measured as the natural logarithm of the number of board members.
Indep	Board Independence: Defined as the proportion of independent directors to the total number of board members.
Top1	Ownership Concentration: Measured as the shareholding percentage of the largest shareholder.
SOE	State Ownership: A binary variable equal to 1 if the firm is state-owned, and 0 otherwise.
Dual	CEO-Chair Duality: A dummy variable equal to 1 if the CEO also serves as the board chair, and 0 otherwise.
Big4	Big Four Auditor: A dummy variable equal to 1 if the firm is audited by one of the Big Four accounting firms, and 0 otherwise.

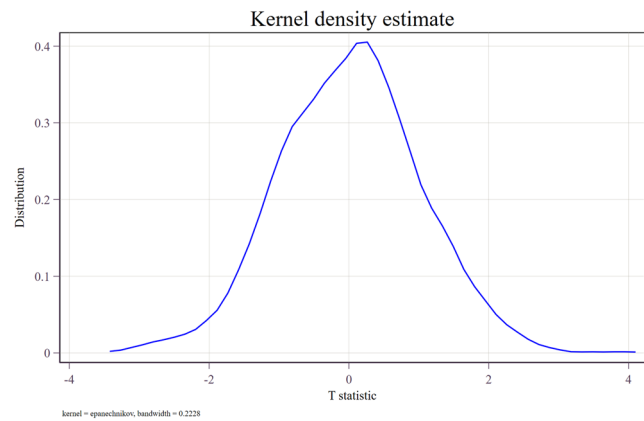


Fig. 1 Placebo test with firms' human capital upgrading as the dependent variable

standard errors clustered at the firm level. Definitions and descriptive statistics for the key variables used in Eq. (1) are summarized in Table 1. The spatial variation of the dependent variable and the key explanatory variable, as well as the descriptive statistics of all variables, are presented in Fig. 1; Table 8.

5 Empirical results and analysis

5.1 Baseline regression results

Table 2 reports the baseline regression results. Column (1) presents the outcome without incorporating control variables or fixed effects. The coefficient of Risk is significantly negative at the 1% level, indicating a preliminary inverse relationship between climate risk and human capital upgrading. Column (2) adds firm and year fixed effects, and the coefficient of Risk remains significantly negative at the 1% level. In Column (3), where all control variables are included, the coefficient of Risk continues to be significantly negative at the 1% level. These findings consistently suggest that, regardless of model specification, climate risk has a robust and statistically significant inhibitory effect on firms' human capital upgrading. This provides preliminary empirical support for Hypothesis 1 proposed in this study. From an economic perspective, the result in Column (3) reveals an estimated coefficient of -0.2192 for the key explanatory variable Risk. The coefficient of the key explanatory variable was -0.2192 , indicating that a 1% increase in the standard deviation of corporate climate risk corresponded to a 2.0178% decrease in the level of human capital upgrading relative to its mean.

Table 2 Baseline results

Variables	(1)	(2)	(3)
	Upgrade	Upgrade	Upgrade
Risk	-0.6758*** (0.0358)	-0.2003*** (0.0520)	-0.2192*** (0.0519)
Size			0.0174*** (0.0047)
Lev			-0.0414** (0.0179)
ROA			0.0249 (0.0244)
Cash			-0.0294* (0.0172)
Age			-0.0841*** (0.0218)
Board			-0.0051 (0.0157)
Indep			-0.0805* (0.0452)
Top1			-0.0176 (0.0366)
Dual			0.0077* (0.0041)
SOE			0.0037 (0.0116)
Big4			0.0061 (0.0144)
Constant	0.5115*** (0.0035)	0.4695*** (0.0046)	0.3884*** (0.1225)
Year FE	No	Yes	Yes
Firm FE	No	Yes	Yes
Observations	29,322	29,322	29,322
Adj_R ²	0.0120	0.7930	0.7947

This table presents the results of the impact of climate risk on corporate human capital upgrading. We control the firm fixed effect and the year fixed effect in the model. Standard errors reported in parentheses are clustered at the firm level, and standard errors are provided in parentheses. ***, **, and * denote the statistical significance of a two-tailed test at the 1%, 5%, and 10% levels respectively

5.2 Addressing endogeneity

5.2.1 Instrumental variable approach

Although our baseline analysis adopts a two-way fixed effects model that mitigates some concerns related to omitted variable bias, potential endogeneity remains a concern in estimating the effect of climate risk on corporate human capital upgrading. This issue primarily arises from two sources:

First, there may be unobserved confounding factors that are not captured by the current model specification. While the analysis controls for a wide range of observable firm-level characteristics, certain latent regional or institutional factors such as local environmental governance capacity, policy transparency, or talent mobility infrastructure

may simultaneously influence both the perceived climate risk and the firm's willingness to invest in human capital, thereby biasing the estimated relationship.

Second, there exists the possibility of reverse causality. In regions with a more advanced stock of human capital, firms may possess stronger capacities for environmental management, data disclosure, and climate risk adaptation. These firm-level characteristics may in turn shape how local governments evaluate and report climate risk, leading to a scenario in which firm attributes influence the observed climate risk index, rather than the other way around.

To address potential endogeneity concerns, this study adopted an instrumental variable (IV) approach, which required the selection of instruments that satisfied both the relevance and exogeneity conditions. Drawing on prior research linking geographical characteristics to environmental risk exposure (He et al. 2025), a geography-based instrument was constructed: the total river length at the city level (River). In terms of relevance, river length, as a stable natural geographical characteristic, was closely associated with a region's hydrological structure, humidity regulation capacity, and the frequency of extreme weather events such as floods and droughts. These factors were intrinsically linked to local physical climate risk. In particular, in areas with high climate risk exposure, a dense river network could amplify the environmental volatility faced by firms, thereby indirectly influencing corporate decisions on workforce stability and human capital planning.

Regarding exogeneity, river length and distribution were determined by natural topography and geomorphology, and were unaffected by contemporary economic activities or corporate decision-making processes. Consequently, they bore no direct causal relationship with firm-level human capital upgrading. Therefore, the instrument met the exclusion restriction.

Since river length is a cross-sectional variable and lacks temporal variation, we followed established econometric practice (Nunn and Qian 2014), by interacting river length with a time-varying climate risk dummy to create a time-varying instrument (River). This constructed instrument enabled the implementation of a two-stage least squares (2SLS) estimation under a fixed effects framework. To Further strengthen the exogeneity assumption, the two-stage regressions additionally controlled for province-level historical economic geography variables, including provincial GDP in 1952 (His_GDP) and the share of primary industry in GDP in 1982 (His_PRI), thereby mitigating potential influences arising from historical industrial agglomeration, labour supply conditions, and other long-term structural factors on the dependent variable.

Table 3 presents the results of the two-stage least squares (2SLS) instrumental variable regression. In the first-stage regression, reported in Column (1), the coefficient on the instrumental variable is significantly positive at the 1% level, consistent with theoretical expectations. The Kleibergen-Paap

Table 3 Endogeneity tests

Variables	(1)	(2)	(3)
	First-stage Regression	Second-stage Regression	Exclusion Test
	Risk	Upgrade	Upgrade
River	0.0033*** (0.0000)		0.00003 (0.0002)
Risk		−0.2274*** (0.0690)	−0.2366*** (0.0601)
His_GDP	Yes	Yes	Yes
His_PRI	Yes	Yes	Yes
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	26,034	26,034	26,034
Adj_R ² /Center R ²	0.7973	0.0126	0.7976
LM F statistic		1373.345***	
Wald statistic		10549.00	

The values in parentheses represent the robust standard errors for clustering at the firm level, and **, *** indicate 5%, 1% significance levels, respectively. The LM F-statistic refers to the Kleibergen-Paap LM F-statistic, while the Wald statistic refers to the Kleibergen-Paap Wald F-statistic

LM statistic is 1373.345 and is statistically significant at the 1% level, indicating that the model is not under-identified. The Kleibergen-Paap rk Wald F-statistic is 10549.00, Substantially exceeding the Stock-Yogo critical value of 16.38 at the 10% level, thereby confirming that weak instrument concerns are not present. In the second-stage regression, reported in Column (2), the coefficient on climate risk remains significantly negative at the 1% level, suggesting that the baseline results are robust after accounting for potential endogeneity issues.

5.2.2 Exogeneity tests for the instrumental variable

To further validate the exclusion restriction of the instrumental variable, we conduct two robustness checks. First, we include the instrumental variable directly as a control in the baseline regression model. As reported in Column (3) of Table 3, the coefficient on the instrument is statistically insignificant, while the estimated coefficient on the key explanatory variable Risk remains significantly negative. This result provides preliminary support for the exogeneity of the instrument, suggesting that it does not exert a direct influence on the dependent variable.

Second, following the placebo testing strategy proposed by prior literature (Acemoglu et al. 2001), we implement a falsification test by randomly reshuffling the values of the instrumental variable to simulate a setting in which no structural correlation exists between the instrument and the endogenous explanatory variable. Based on this reshuffled variable, we construct a simplified regression model Linking the instrument to firm-level human capital upgrading and repeat the estimation 1000 times. As illustrated in Fig. 1, the distribution of placebo regression coefficients is centered around zero, with most associated P-values exceeding 0.1. These findings suggest that the instrument does not

have a statistically significant relationship with the outcome variable under random assignment, thereby reinforcing the validity of our instrument.

5.3 Robustness tests

5.3.1 Alternative measures of the dependent variable

To validate the robustness of the main findings, we first employ an alternative proxy for firms' human capital upgrading based on job functions, following prior literature (Li et al. 2025a, b; Ni 2025). Specifically, we redefine the dependent variable as the proportion of technical personnel in total employees, capturing the intensity of human capital upgrading from a functional perspective. Column (1) of Table 4 reports the regression results. The estimated coefficient of Risk remains significantly negative at the 1% level, confirming the validity of the baseline conclusion.

5.3.2 Alternative measures of the core explanatory variable

Next, we replace the firm-level climate risk indicator with a city-level index of physical climate risk, drawing on the measurement approach proposed by prior literature (He et al. 2025). This index is constructed using annual observations of four categories of extreme weather events: days of extreme low temperature, high temperature, heavy precipitation, and severe drought. Each indicator is standardized, and their arithmetic mean is used to represent the overall level of physical climate risk in each city for a given year. Column (2) of Table 4 presents the regression results using this alternative specification. The coefficient on climate risk

Table 4 Robustness tests

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Upgrade_new	Upgrade	Upgrade	Upgrade	Upgrade	Upgrade	Upgrade
Risk	−0.0995** (0.0389)		−0.2192*** (0.0513)	−0.2192*** (0.0645)	−0.2192*** (0.0725)	−0.3803*** (0.0742)	−0.2173*** (0.0594)
Risk_new		−0.0010*** (0.0002)					
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	29,322	20,954	29,322	29,317	29,317	11,471	21,760
Adj. R ²	0.7387	0.8000	0.7947	0.7947	0.7947	0.7284	0.7867

The values in parentheses represent the robust standard errors for clustering at the firm level, and *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively

remains significantly negative at the 1% level, further reinforcing the robustness of our core findings.

5.3.3 Changing the clustering hierarchy

To further assess the robustness of our regression results, we re-estimate the baseline model using alternative clustering dimensions to address potential biases arising from intra-group correlation in the error terms. First, we cluster standard errors at the industry level to account for correlated shocks across firms sharing similar technological features, market conditions, or regulatory environments within the same sector. The results, reported in Column (3) of Table 4, remain robust and significant.

Second, considering that local climate conditions, regional economic policies, and infrastructure development may generate spatially correlated shocks at the city level, we additionally cluster standard errors by city. As shown in Column (4) of Table 4, the main findings are preserved.

Finally, to ensure robustness against broader institutional and structural heterogeneity, we further cluster standard errors at the provincial level. This adjustment accounts for potential common shocks related to regional climate governance, industrial policy, or administrative practices. Column (5) of Table 4 reports the results, which again confirm that the estimated coefficient on Risk remains significantly negative at the 1% level. These findings collectively reinforce the reliability and robustness of our baseline conclusion.

5.3.4 Sample restructuring tests

To further verify the robustness of our baseline results, we conduct supplementary analyses by altering the sample along two key dimensions: city administrative status and temporal shocks. First, recognizing that municipalities directly under the central government, sub-provincial cities, and provincial capitals in China typically enjoy superior resource endowments, policy support, and governance capacity, we address the concern that these cities may systematically influence

firms' perceptions of and responses to climate risk. To mitigate this potential structural bias, we exclude all observations from four municipalities, fifteen sub-provincial cities, and all provincial capitals, and re-estimate the model. The results, reported in Column (6) of Table 4, remain consistent with our baseline findings.

Second, in light of the unprecedented economic disruption triggered by the COVID-19 pandemic in 2020 which may have altered firms' labor investment strategies in ways unrelated to climate risk we exclude all post-2020 observations and re-conduct the regression analysis. As shown in Column (7) of Table 4, the main findings remain robust, lending further empirical support to the validity of our baseline conclusion.

6 Further analyses

6.1 Mechanism tests

This paper argues that when firms are exposed to elevated levels of climate risk, corporate managers motivated by risk aversion are likely to alter their investment strategies, particularly by reducing growth-oriented investments. To empirically test this mechanism, we examine the impact of climate risk across three specific dimensions.

6.1.1 Heightened perception of uncertainty

Firms' subjective perceptions of external uncertainty serve as a fundamental cognitive basis for strategic investment decisions. Prior research suggests that heightened uncertainty undermines the predictability of future returns, thereby reducing firms' willingness to commit to long-term strategic investments, such as human capital upgrading (Li et al. 2021). To verify this channel, we adopt a firm-level uncertainty perception index (FEPUI), following the methodological framework established in the literature, to

Table 5 Mechanism analysis

	(1)	(2)	(3)	(4)	(5)	(6)
	FEP	Upgrade	Management	Upgrade	FC	Upgrade
Risk	0.0667*** (0.0224)	−0.2121*** (0.0529)	1.0475*** (0.1658)	−0.1895*** (0.0516)	0.7554** (0.3747)	−0.2016*** (0.0537)
FEP		−0.1373*** (0.0176)				
Management				−0.0264*** (0.0025)		
FC						−0.0106*** (0.0012)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	27,156	27,156	29,215	29,215	26,039	26,039
Adj_R ²	0.4016	0.7902	0.4374	0.7979	0.7892	0.7927

The values in parentheses represent the robust standard errors for clustering at the firm level, and ** and *** indicate 5% and 1% significance levels, respectively

capture the extent to which climate risk disrupts firms' forward-looking expectations.

As shown in Column (1) of Table 5, the estimated coefficient on the climate risk variable was significantly positive at the 1% level, indicating that higher levels of climate risk were associated with increased perceived uncertainty regarding the firm's future operating environment. In Column (2), the regression coefficient on perceived uncertainty about the future operating environment was significantly negative, suggesting that climate risk suppressed firms' investment in human capital upgrading by heightening their perception of future environmental uncertainty. The result confirmed Hypothesis 2 of this study and identified a key cognitive pathway through which climate risk influenced firms' long-term strategic investment decisions.

6.1.2 Reinforcing managerial myopia

In the context of disrupted expectations, managerial responses serve as a critical behavioral channel through which external shocks, such as climate risk, affect firm-level strategic decisions. Elevated climate risk may prompt managerial "myopic" behavior, whereby executives motivated by risk aversion reorient corporate priorities from long-term capability building toward short-term performance outcomes. To empirically test this mechanism, we construct a managerial myopia index (Management) following prior literature (Zhu et al. 2025), defined as the proportion of short-term-oriented keywords excluding tabular content in the total text of corporate annual reports.

As reported in Column (3) of Table 5, the coefficient on climate risk is significantly positive at the 1% level, indicating that climate risk meaningfully heightens managerial tendencies toward short-termism. In Column (4), the regression coefficient on managerial short-termism was significantly

negative, indicating that climate risk suppressed firms' human capital upgrading by intensifying managerial tendencies toward short-termism, thereby confirming Hypothesis 3 of this study. This finding underscores the role of managerial short-termism as a behavioural channel through which climate risk translates environmental uncertainty into reduced long-term commitments to human capital upgrading.

6.1.3 Intensifying financial constraints

External financing capacity is a critical enabler of firms' long-term strategic investments. Climate risk can tighten firms' financial constraints by raising default probabilities, lowering credit ratings, and increasing risk premiums (Naseer et al. 2025). To examine this pathway, we introduce a firm-level financial constraint index (FC), proxied by the widely used Kaplan-Zingales (KZ) index. As shown in Column (5) of Table 5, the coefficient on climate risk was significantly positive at the 5% level, indicating that heightened climate risk conditions indeed exacerbated firms' financial constraints. Column (6) further revealed that the regression coefficient on financial constraints was significantly negative, suggesting that climate risk suppressed firms' human capital upgrading by tightening their financial constraints, thereby confirming Hypothesis 4 of this study. This finding highlights the role of capital market frictions in mediating the adverse effects of environmental uncertainty on strategic resource allocation.

Taken together, the mechanism analysis provides robust evidence that climate risk hampers firms' human capital upgrading through three interrelated pathways: (1) increasing perceived environmental uncertainty, (2) reinforcing managerial myopia, and (3) intensifying financial constraints. These findings offer a nuanced understanding of how firms adapt (or fail to adapt) their labor strategies under

systemic climate threats, contributing to the literature on climate risk, corporate governance, and sustainable workforce development.

6.2 Heterogeneity analysis

To further explore the heterogeneous effects of climate risk on firms' human capital upgrading strategies, we conduct a subgroup analysis based on firm-level and regional characteristics.

6.2.1 Heterogeneity by ownership structure

We begin by partitioning the sample into state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs) and estimate separate regressions to identify whether the effect of climate risk varies by ownership status. Columns (1) and (2) of Table 6 report the results. The estimates show that the negative effect of climate risk on human capital upgrading is more pronounced and statistically significant in the Sub-sample of non-SOEs. Moreover, the difference in coefficients between the two groups is significant at the 1% level.

This result is both intuitive and economically meaningful. Compared with SOEs, non-SOEs generally operate with weaker institutional support, fewer financing channels, and more limited capacity to absorb external shocks. As a result, when climate risk intensifies, non-SOEs are more likely to adopt precautionary contraction strategies, prioritizing short-term liquidity and operational survival over long-term investments such as human capital upgrading. Furthermore, non-SOEs are typically governed by incentive structures that emphasize short-term performance metrics. Under uncertain conditions, their managerial responses tend to be more rapid and pronounced, thereby amplifying the curtailment of human capital upgrading. In contrast, SOEs benefit from stronger policy backing and access to governmental or quasi-governmental resource buffers. These

advantages allow them to partially absorb the uncertainty associated with climate risk and maintain relatively stable investments in long-term workforce development.

6.2.2 Heterogeneity by degree of financial constraint

To further investigate how a firm's financing capacity moderates the relationship between climate risk and human capital upgrading, we adopt an established methodological approach and use the median value of the SA index to split the sample into two groups: high financial constraint and low financial constraint. Columns (3) and (4) of Table 6 present the regression results for each group.

The findings indicate that the negative impact of climate risk on human capital upgrading is significantly more pronounced among firms with higher financial constraints, and the inter-group difference is statistically significant. This pattern suggests that the suppressive effect of climate risk on human capital upgrading is amplified under tighter financing conditions.

The economic rationale is that, in the presence of financial frictions, firms rely more heavily on internally generated cash flows to support strategic investments. As climate risk intensifies and future returns become more uncertain, firms are more likely to reallocate limited financial resources toward immediate operational needs and liquidity preservation. In this setting, human capital investments characterized by long payback periods and uncertain benefits are often deemed discretionary and thus subject to early-stage cutbacks.

This effect is particularly salient for firms with limited access to external financing and weaker shock absorption capacity. For these firms, climate risk further exacerbates financial fragility, crowding out expenditures on training, skill enhancement, and organizational development. In contrast, firms with lower financial constraints typically possess greater capital buffers and enjoy easier access to financing, which enables them to better withstand climate-related uncertainty and maintain stable long-term investment in human capital.

6.2.3 Heterogeneity by regional human capital endowment

To further explore how regional differences in human capital Supply shape the impact of climate risk on corporate investment in human capital, we conduct a Heterogeneity analysis based on regional talent endowment. Specifically, we use the number of higher education students per 10,000 residents as a proxy for regional human capital capacity. Firms are divided into two groups high and low human capital endowment regions based on the median value of this indicator, and separate regressions are performed accordingly. The results are reported in Columns (1) and (2) of Table 7.

Table 6 Heterogeneity by firm characteristics

Variable	(1)	(2)	(3)	(4)
	SOEs	Non-SOEs	High Financing Constraints	Low Financing Constraints
	Upgrade	Upgrade	Upgrade	Upgrade
Risk	-0.0343 (0.0813)	-0.3076*** (0.0661)	-0.2326*** (0.0665)	-0.0634 (0.0643)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	9663	19,659	14,670	14,652
Adj_R ²	0.7771	0.8143	0.8381	0.8399
P statistic	0.000		0.000	

The values in parentheses represent the robust standard errors for clustering at the firm level, and *** indicate 1% significance levels, respectively. The p-value is obtained from a Fisher's permutation test with 500 replications

The findings show that the negative effect of climate risk on human capital upgrading is significantly more pronounced in regions with weaker human capital endowments. The intergroup coefficient difference is statistically significant, confirming the robustness of the observed heterogeneity.

This result can be explained by the structural disadvantages typically faced by talent-constrained regions, such as shortages of high-skilled labor, underdeveloped training systems, and limited knowledge spillovers. In such contexts, firms incur higher marginal costs in attracting and retaining qualified workers, making them more vulnerable to external shocks. When faced with heightened uncertainty and operational pressure caused by climate risk, these firms are more likely to adopt defensive strategies, including cutting training budgets and postponing skill enhancement initiatives thereby exhibiting a more substantial contraction in human capital investment.

In contrast, firms operating in regions with stronger human capital endowments benefit from better access to local educational institutions and talent pools. These firms face lower marginal costs in sustaining human capital upgrading and demonstrate greater resilience and adaptive capacity in the face of environmental uncertainty.

6.2.4 Heterogeneity by regional exposure to physical climate risk

To further investigate whether the impact of climate risk on corporate human capital upgrading varies with the severity of the external physical climate environment, we conduct a heterogeneity analysis based on firms' regional exposure to physical climate risks. Specifically, we construct a city-level physical climate risk index using historical data on four types of extreme weather events: extreme high temperature days, extreme low temperature days, extreme precipitation days, and extreme drought days. Each indicator is standardized

and averaged to derive a composite index. Based on the median value of this index, cities are categorized into high and low physical climate risk exposure groups. We then perform separate regressions on firms located in each group.

The estimation results, reported in Columns (7) and (8) of Table 7, show that the negative effect of climate risk on human capital upgrading is significantly stronger in regions with higher exposure to physical climate risk. The coefficient difference between the two groups is statistically significant at the 5% level.

This finding can be explained by the economic mechanism that firms operating in regions with higher exposure to climate-related physical hazards are more frequently and severely affected by extreme weather events. These disturbances raise operational uncertainty and increase the costs of production coordination, thereby inducing firms to adopt more conservative financial strategies. In such contexts, long-term investments with deferred payoffs such as those in human capital upgrading are more likely to be deprioritized or cut. In contrast, firms in regions with lower physical climate risk face fewer environmental disruptions and enjoy more stable production conditions. This stability enhances their confidence in long-term returns, increasing the likelihood of sustained investment in employee training, skill development, and workforce restructuring.

7 Conclusion and policy implications

As a salient source of external uncertainty in the context of green transition, climate risk not only reshapes corporate expectations, managerial behaviors, and resource allocation strategies but may also impede firms' human capital upgrading through various micro-level mechanisms. Despite its growing relevance, this pathway remains underexplored in existing Literature. Using a panel dataset of Chinese A-share Listed firms from 2008 to 2022, this study constructs a

Table 7 Heterogeneity by regional characteristics

Variable	(1)	(2)	(3)	(4)
	Regions with Strong Talent Supply Capacity	Regions with Weak Talent Supply Capacity	Regions with High Physical Climate Risk Exposure	Regions with Low Physical Climate Risk Exposure
	Upgrade	Upgrade	Upgrade	Upgrade
Risk	-0.0991 (0.0695)	-0.3369*** (0.0721)	-0.2510*** (0.0627)	-0.1249 (0.0792)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	16,427	12,895	18,530	10,792
Adj_R ²	0.7986	0.7726	0.7830	0.8068
P statistic	0.000		0.014	

The values in parentheses represent the robust standard errors for clustering at the firm level, and *** indicate 1% significance levels, respectively. The p-value is obtained from a Fisher's permutation test with 500 replications

two-way fixed effects model to systematically examine the impact of climate risk on corporate human capital upgrading and its underlying mechanisms.

The empirical results reveal that climate risk significantly suppresses firms' human capital upgrading efforts. This conclusion remains robust across a series of empirical strategies, including instrumental variable (IV) regressions, exclusion restriction tests, lagged dependent variable models, propensity score matching (PSM), difference-in-differences (DID) analysis, and multi-dimensional fixed effects adjustments. Heterogeneity analyses further show that the negative effect is more pronounced among non-state-owned enterprises, firms facing higher financing constraints, those operating in regions with weaker human capital endowments, and those exposed to greater levels of physical climate risk.

Mechanism analyses identify three distinct channels through which climate risk affects firms' human capital strategies: (1) cognitively, it raises firms' perceptions of environmental uncertainty, thereby weakening long-term investment intentions; (2) behaviorally, it reinforces managerial short-termism, leading to cuts in longer-term strategic expenditures; and (3) financially, it intensifies firms' capital constraints, reducing their capacity to sustain investments in workforce development.

These findings provide novel micro-level evidence for understanding how climate-induced uncertainty affects firms' long-term capability building. They also offer actionable insights for policymakers seeking to optimize human capital allocation and strengthen corporate climate resilience in the pursuit of sustainable development.

Based on the findings of this study, several policy implications emerge:

First, enhancing the resilience of corporate human capital is essential for building a strategic foundation for factor upgrading under climate adaptation. The study reveals that climate risk significantly hampers firms' human capital upgrading, suggesting that under heightened uncertainty, firms are prone to scale back human capital investments, undermining their long-term capability building. In light of China's "Dual Carbon" strategy, the government should accelerate the development of an integrated human capital support system covering vocational training, technical education, and green transition. Targeted fiscal incentives, preferential tax policies, and dedicated funding programs should be implemented to support firms in cultivating high-skilled labor and optimizing workforce structures. Particular attention should be paid to ensuring accessibility and affordability of training support for small and medium-sized enterprises and growth-oriented firms, helping them maintain strategic continuity in human capital investment even amid external shocks.

Second, a more robust framework for expectation management and resource support is needed to mitigate the systemic transmission of climate risk within firms. The mechanism analysis reveals that climate risk affects firms primarily through

three channels: heightened environmental uncertainty, increased managerial short-termism, and tightened financing constraints. Accordingly, policy responses should target improvements in three key areas: information, incentives, and finance. First, environmental and climate-related disclosure requirements should be strengthened, and early warning systems established to improve firms' ability to anticipate and respond to climate shocks. Second, corporate governance frameworks should shift toward long-term performance evaluation, correcting managerial tendencies to reduce human capital investments under short-term pressure. Third, green financing channels must be expanded through innovations such as sustainability-linked bonds and dedicated human capital loans, ensuring that firms have access to predictable, affordable financing for workforce development. These coordinated interventions would help establish a tripartite "expectation–behavior–resource" adaptation support system.

Third, differentiated policy approaches tailored to firm characteristics and regional contexts are essential for enhancing the adaptive capacity of vulnerable groups and highly exposed regions. The heterogeneity analysis shows that the negative impact of climate risk is more pronounced for non-state-owned firms, financially constrained firms, firms in regions with weaker talent endowments, and those located in areas with high exposure to physical climate risk. A stratified policy support framework should be designed along both institutional and resource dimensions. For severely impacted firms, a human capital upgrading fund with a green transformation mandate could be established to support organisational restructuring and workforce retraining. For high-risk regions, particularly talent-deficient western provinces, local governments could provide targeted subsidies, training vouchers, and relocation incentives to attract and retain skilled labour. Green insurance mechanisms and policy-oriented financial tools should also be developed to enhance the capacity for safe and strategic human capital investment in these areas. Finally, firms should be encouraged to develop climate-resilient human capital strategies based on their unique resource endowments, building multi-tier workforce structures and counter-cyclical talent reserves to improve organisational robustness and adaptability under long-term environmental uncertainty.

Fourth, beyond policy-level interventions, firms themselves should adopt proactive strategies to mitigate the adverse impact of climate risk on human capital upgrading. Management should integrate climate considerations into workforce planning through measures such as internal green skills training programmes, scenario-based resilience planning, and climate-linked human resource incentive systems. Establishing multi-tier skill reserves and embedding sustainability-oriented performance metrics into promotion and compensation schemes can encourage employees to acquire and apply climate-relevant competencies. Additionally, firms could enhance organisational adaptability by incorporating climate risk assessments into recruitment, training, and retention policies,

thereby aligning human capital strategies with long-term environmental challenges.

Appendix

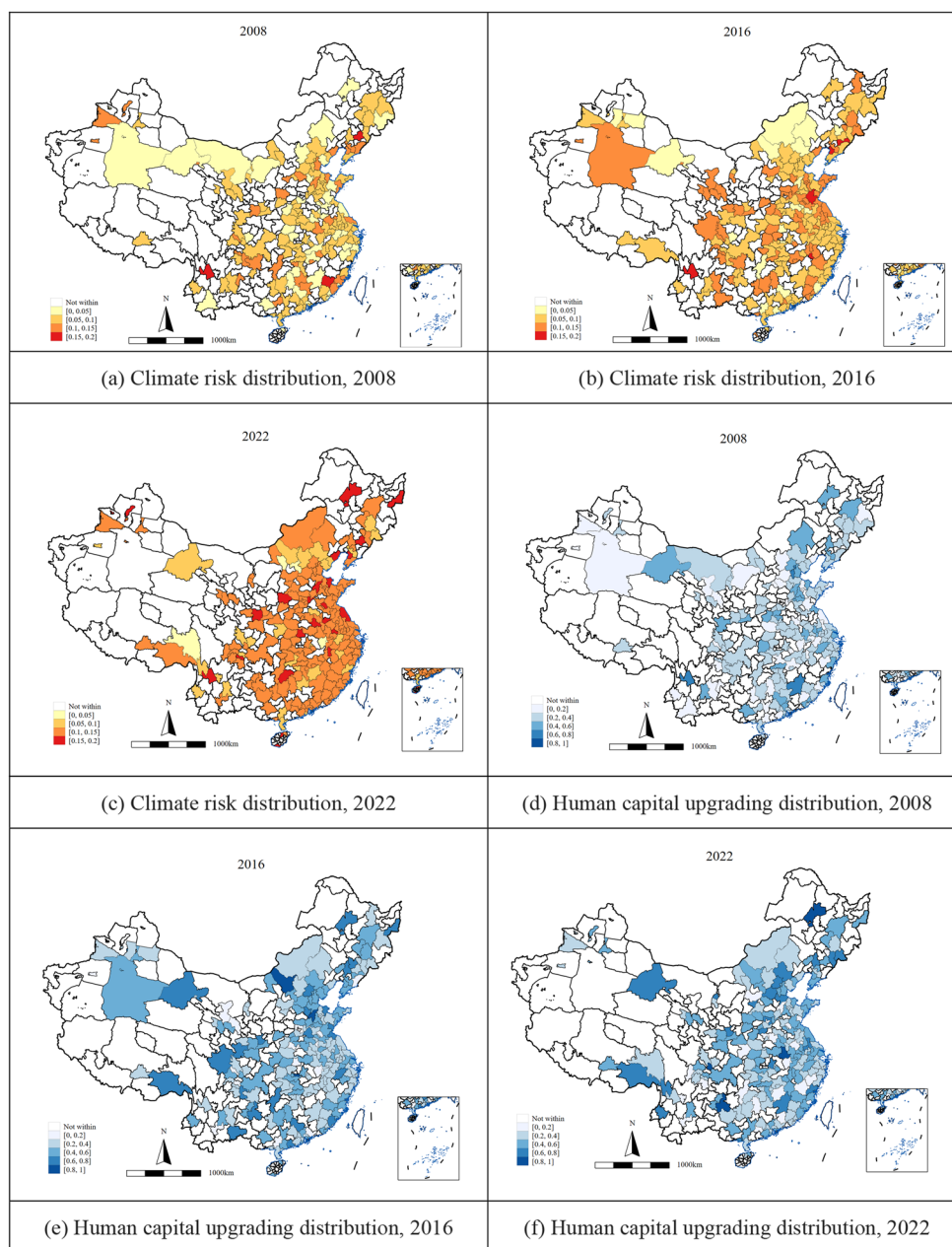
Climate risk and Human capital upgrading distribution

An examination of the spatial distribution of average climate risk and human capital upgrading among Chinese A-share listed firms at the prefecture-city level in 2008, 2016, and

2022 reveals notable temporal dynamics for both variables, as illustrated in Fig. 2.

For climate risk, the spatial pattern was characterised by a sustained overall increase, a gradual decline from east to west, and an expansion from coastal to inland regions. In 2008, high-risk areas were concentrated in a belt along the eastern coast, particularly in the Yangtze River Delta, the Pearl River Delta, and parts of the Bohai Rim. By 2016, these high-risk areas had extended inland along the Yangtze River Economic Belt, with additional medium-to-high risk clusters emerging in the Chengdu-Chongqing urban agglomeration, the North China Plain, and parts of Northeast China. By 2022, high-risk areas displayed greater continuity

Fig. 2 Spatial distribution of climate risk and human capital upgrading for Chinese A-share listed firms (2008, 2016, 2022)



in the eastern coastal region, the Pearl River Delta, the Beijing–Tianjin–Hebei region, and the Liaodong Peninsula, with sporadic high values also appearing in parts of Northwest and Northeast China. The overall pattern shifted from “coastal concentration” to “multi-centre diffusion.”

In contrast, the spatial pattern of human capital upgrading was characterised by a steady overall increase, a pronounced advantage in the eastern region, and gradual catch-up in the central and western regions. In 2008, high-value areas were mainly concentrated in developed eastern coastal urban clusters such as the Yangtze River Delta, the Pearl River Delta, and the Bohai Rim, with relatively low levels in most central and western regions. By 2016, human capital upgrading levels had generally improved nationwide, with high-value areas expanding in the eastern coastal region and new medium-to-high value clusters emerging in the Chengdu–Chongqing urban agglomeration, the middle reaches of the Yangtze River, and parts of Northeast China. In 2022, the eastern coastal high-value areas maintained their lead, while more continuous medium-to-high value distributions appeared in the Beijing–Tianjin–Hebei region, the middle reaches of the Yangtze River, and the Chengdu–Chongqing area, with sporadic high values also observed in parts of Northwest and Northeast China.

Descriptive Statistics

Table 8 presents the descriptive statistics of the main variables used in this study. The dependent variable, Upgrade, ranges from 0.0208 to 0.9891 with a standard deviation of 0.2561, indicating considerable heterogeneity in human capital levels across firms. The mean value of Risk is 0.0882, suggesting that most firms exhibit relatively low levels of perceived climate risk. However, the wide gap between its minimum and maximum values reflects substantial variation in firms’ exposure to or recognition of climate-related risks. For firm performance metrics, the coefficient of variation

for ROA is 1.90, and for Cash, it is 1.63, implying that firms differ significantly in terms of profitability and operational liquidity. Regarding corporate governance characteristics, the average value of Indep is 0.3754, suggesting that on average, independent directors constitute approximately one-third of the board. The mean of Top1 is 0.3426, indicating that the largest shareholder holds, on average, 34.26% of total shares. Additionally, the variable SOE has a mean of 0.3295, indicating that 32.95% of the sample firms are state-owned enterprises. The variable Big4 has a mean value of 0.0540, suggesting that only 5.4% of the sample firms are audited by one of the Big Four accounting firms.

Supplementary robustness tests

Controlling for multi-dimensional fixed effects

To further enhance the precision of causal identification, we incorporate higher-dimensional interaction fixed effects into the baseline regression model to account for potential structural heterogeneity across time and space. Specifically, we sequentially introduce three types of interaction fixed effects: year-industry, year-province, and province-industry. We also estimate an extended model that includes all three simultaneously.

First, year×industry fixed effects control for common shocks experienced by firms within the same industry in a given year such as macroeconomic conditions, cyclical fluctuations, or industry-specific policy adjustments that may systematically influence corporate behavior. Second, year×province fixed effects help absorb unobserved regional disturbances stemming from heterogeneous local fiscal policies, environmental regulation intensity, or labor market dynamics across provinces over time. Third, province×industry fixed effects account for long-standing structural differences among region-industry pairs,

Table 8 Descriptive statistics

Variables	N	Mean	p50	SD	Min	Max
Upgrade	29,322	0.4519	0.4062	0.2561	0.0208	0.9891
Risk	29,322	0.0882	0.0837	0.0416	0.0122	0.1803
Size	29,322	21.9437	21.7746	1.2233	19.3129	26.4523
Lev	29,322	0.4066	0.3912	0.2111	0.0278	0.9343
ROA	29,322	0.0369	0.0390	0.0702	−0.5779	0.2203
Cash	29,322	0.0448	0.0447	0.0732	−0.2262	0.2822
Age	29,322	2.8495	2.8904	0.3705	1.0986	3.6109
Board	29,322	2.1173	2.1972	0.1975	1.6094	2.7081
Indep	29,322	0.3754	0.3571	0.0537	0.2500	0.6000
Top1	29,322	0.3426	0.3211	0.1456	0.0806	0.7579
Dual	29,322	0.3025	0.0000	0.4593	0.0000	1.0000
SOE	29,322	0.3295	0.0000	0.4701	0.0000	1.0000
Big4	29,322	0.0540	0.0000	0.2259	0.0000	1.0000

Table 9 Controlling for multidimensional fixed effects

Variable	(1)	(2)	(3)	(4)
	Upgrade	Upgrade	Upgrade	Upgrade
Risk	−0.1700*** (0.0455)	−0.2305*** (0.0517)	−0.1044** (0.0419)	−0.1304*** (0.0420)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year×Industry	Yes	No	No	Yes
Year×Province	No	Yes	No	Yes
Province×Industry	No	No	Yes	Yes
Observations	29,301	29,317	29,293	29,271
Adj_R ²	0.8087	0.7968	0.8227	0.8266

Table 10 Other endogeneity tests

Variables	(1)	(2)	(3)
	Including One-period Lag of Upgrade	PSM	DID
	Upgrade	Upgrade	Upgrade
Risk	−0.1103*** (0.0310)	−0.2192*** (0.0519)	
Upgrade_lag	0.6043*** (0.0108)		
DID			−0.0069** (0.0034)
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	23,481	29,322	29,322
Adj_R ²	0.8746	0.7947	0.7943

including variations in resource endowment, industrial agglomeration, or green transition pathways, thereby mitigating the confounding influence of static heterogeneity.

By simultaneously including these three layers of fixed effects, the model achieves a more comprehensive control over region, industry, and time-specific confounders, substantially improving the credibility of causal inference. As reported in columns (1) through (4) of Table 9, the estimated coefficient on the climate risk variable remains significantly negative at the 1% level across all model specifications, reinforcing the robustness of our core findings.

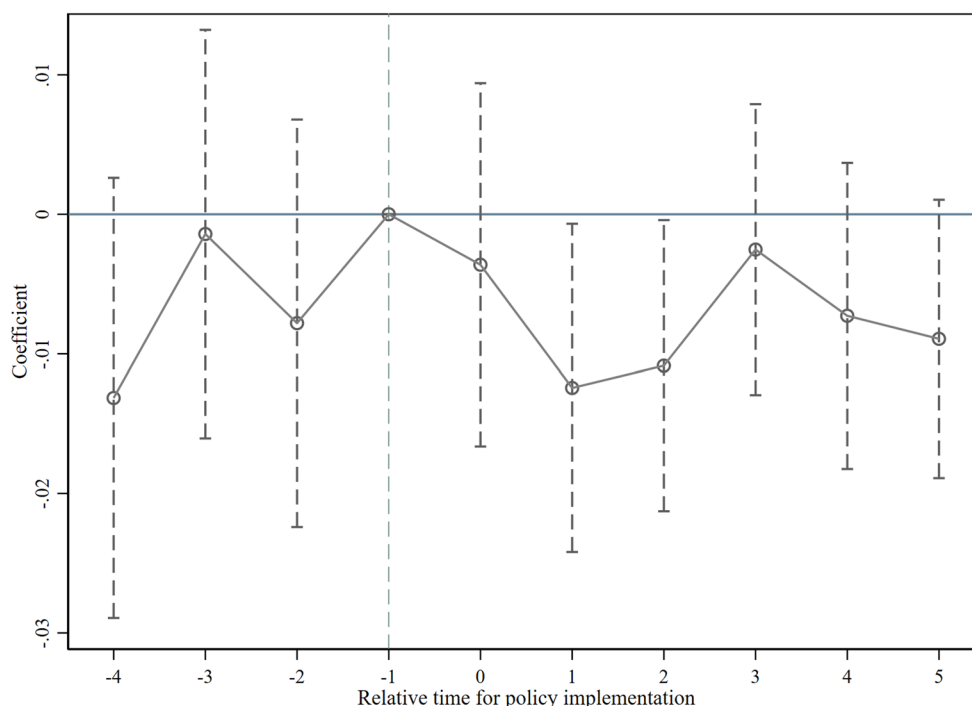
Incorporating the lagged dependent variable

To further mitigate potential endogeneity concerns, we re-estimate the baseline regression model by including the one-period lag of the dependent variable as an additional control. The inclusion of the lagged term serves two purposes: it captures the dynamic inertia in firms' human capital upgrading and accounts for potential path dependency driven by firm-specific characteristics. As reported in Column (1) of Table 10, even after controlling for the lagged dependent variable, the coefficient on climate risk remains significantly negative at the 1% level. This finding suggests that the adverse effect of climate risk on human capital

upgrading persists despite controlling for dynamic adjustment processes, thereby providing additional support for the robustness of our core results.

Propensity score matching (PSM)

To further verify the robustness of the baseline regression results and alleviate potential sample selection bias, we employ the Propensity Score Matching (PSM) method to re-estimate the effect of climate risk exposure. Specifically, we divide the full sample into a treatment group (firms with above-median climate risk) and a control group (firms with below-median climate risk) based on the median value of the climate risk variable. Using all control variables from the baseline model as covariates, we estimate each firm's propensity score and implement 1:1 nearest-neighbor matching to construct a more balanced sample for comparison. We then re-estimate the regression model using the matched sample. As shown in Column (2) of Table 10, the coefficient on climate risk remains negative and statistically significant at the 1% level. This result suggests that the negative effect of climate risk on corporate human capital upgrading persists even after controlling for observable firm characteristics and correcting for potential selection bias.

Fig. 3 Parallel trend test for DID

Difference-in-differences (DID) analysis

To further validate the robustness of the baseline findings, this study employs a difference-in-differences (DID) approach, drawing on identification strategies used in prior research (Ginglinger and Moreau 2023). Specifically, we treat the ratification of the Paris Agreement at the end of 2015 as an exogenous policy shock. The Agreement is widely regarded as a watershed moment in the institutionalization of global climate governance, offering a well-defined external event to capture the intensification of climate-related regulatory pressure. In our DID framework, we define a time dummy variable, *Post*, which equals 1 for 2015 and subsequent years, and 0 otherwise. We then categorize firms into treatment and control groups based on the 60th percentile of the climate risk distribution: firms located in high-risk areas are assigned to the treatment group, and those in low-risk areas to the control group. The interaction term (DID) between *Post* and the treatment indicator captures the differential effect of heightened climate risk following the policy shock.

Column (3) of Table 10 reports the results. The coefficient on the DID variable is significantly negative at the 1% level, indicating that firms in high climate-risk regions experienced a marked decline in human capital upgrading relative to others after the signing of the Paris Agreement. Furthermore, Fig. 3 parallel trends tests support the validity of the identifying assumption, confirming that the observed effect is attributable to the policy shock rather than pre-existing differences.

Acknowledgements The authors are grateful to the insightful comments suggested by the editor and the anonymous reviewers.

Author contributions J H: writing and method D W: design and investigation H Z: writing S M: revision and design.

Funding This research was funded by National Statistical Science Research Major Project of China, grant number 2024LD003. This research was funded by the Innovation Project of Guangxi Graduate Education of China, grant number YCBZ2024021.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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