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Carbon risk and corporate bankruptcy pressure: evidence from a quasi-natural experiment based on the Paris agreement

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Green and low-carbon development transformation of enterprises is of great significance to climate governance and sustainable economic development. It is a realistic problem worth to study whether carbon risk will affect the bankruptcy pressure of corporates. This paper empirically analyzes the impact of carbon risk shocks on the corporates bankruptcy pressure based on the quasi-natural experiment of the implementation of the Paris Agreement. The results indicated that carbon risk significantly alleviated corporates bankruptcy pressure. Specifically, mechanistic analysis uncovered that the increase in carbon risk may reduce the bankruptcy pressure of corporates was mediated by lowering corporate financing costs and elevating green innovation levels. Finally, it was found through the heterogeneity analysis that the negative correlation between carbon risk and bankruptcy pressure was more pronounced for non-state-owned enterprises, small-scale corporations, and companies located in highly competitive industries.

KEYWORDS

Paris climate agreement, carbon risk, bankruptcy pressure, financial constraints, green innovation

1 Introduction

Climate change caused by carbon emissions is threatening human society and requires active coping from all countries in the world (Subramaniam et al., 2015; Anastasiou et al., 2024). The Paris Agreement signed in December 2015 is a legally binding climate agreement which marks a new historical stage in global climate governance (Bose et al., 2021; Dewaelheyns et al., 2023). As a responsible global player, the Chinese government implements the Paris Agreement actively that achieved remarkable results in key areas such as strategic mechanism building, industrial structure optimization, carbon market construction, and social awareness raising. Meanwhile accession to the Paris Agreement reflects determination and efforts of China to promote green and low-carbon development and also sends a signal that China would strengthen carbon emission supervision that undoubtedly would increase the uncertainty of the policy environment and then makes enterprises face a new and more severe carbon risk situation. Specifically, carbon risk includes policy risk, market risk, technical risk, economic risk and supply chain risk that arise from the uncertainty of enterprise's expected and regulatory activities in the transition to a low-carbon economy (Hoffmann and Busch, 2008; Labatt and White, 2011). Therefore, it is a major realistic problem for enterprises to take the path of green and low-carbon development while avoiding the potential impact from carbon risk.

Based on the above background, it is an important theoretical basis for the low-carbon development path of Chinese enterprises to investigate the relationship between carbon risk and firm bankruptcy pressure. Whether the increase of carbon risk would increase the bankruptcy pressure of corporate has been widely concerned by the academic circle. To address this gap, this paper formulate a competitive hypothesis regarding the potential ways in which carbon risk could influence corporate insolvency pressure. On one hand, certain studies suggest that carbon risk may theoretically exacerbate the financial leverage of enterprises (Dumrose and Hock, 2023), elevate both equity and debt costs (Chava, 2014), and increase operational expenses for businesses (Gorgen et al., 2020; Zhang and Du, 2020). This risk arises from the fact that high-carbon companies face greater financial penalties when mandated to reduce emissions (Bolton and Kacperczyk, 2021), with escalating costs potentially rendering these firms unsustainably profitable, thereby jeopardizing their capital structure and heightening bankruptcy risks. Therefore, a perspective grounded in cost theory posits that if companies are compelled to lower carbon emissions due to stricter environmental regulations, they will incur higher operating costs alongside more volatile cash flows (Subramaniam et al., 2015). Under the strain of carbon risk, enterprises must implement measures such as production reductions to alter resource allocation efficiency that could adversely affect innovation capabilities (Millimet et al., 2009; Greenstone et al., 2012). On the other hand, as carbon risk increases, the constriction of financing availability for carbon-intensive industries effectively diminishes the financial leverage, alters the debt maturity structure, and curtails investment expenditures of polluting enterprises (Wang et al., 2019). Additionally, Nguyen and Phan (2020) demonstrate that carbon risk leads to a reduction in financial leverage within carbon-intensive firms, with this effect being more pronounced for those facing greater financial constraints. Furthermore, such as the green credit policy implemented in response to carbon risk also can modify the debt maturity structure and mitigate excessive investment behaviors among these enterprises (Liu et al., 2017). It is worth noting that according to Porter's hypothesis, enterprises would escalate their investments in research, development, and innovation in order to diminish production costs and enhance competitiveness (Wang and Sun, 2021; Wu and Lin, 2022). This emphasis on process and product innovation may alleviate some of the negative impacts associated with rising costs due to carbon risk and ultimately lessen the financial pressures that could lead firms toward bankruptcy (Porter, 1996; Bai and Tian, 2020). Given the divergent predictions present within existing theories regarding reduction versus enhancement effects, empirical data is crucial for assessing the impact of carbon risk on corporate bankruptcy pressure.

Therefore, in order to test the hypothesis above, this paper applies a difference-in-differences (DID) method using the data of Chinese companies listed on the Shanghai and Shenzhen stock exchanges from 2011 to 2021 to explore the impact of carbon risk on corporate bankruptcy pressure and its possible influence channels. Different from previous studies, this paper mainly has the following contributions: firstly, although previous research has investigated some other micro-effects of carbon risk, the effect of carbon risk on corporate bankruptcy pressure has not yet been considered. This paper enhances understanding of the micro-effects of corporate bankruptcy pressure by examining carbon risk management behaviors and furnishes micro-empirical evidence that contributes to the evaluation of the effects of carbon risk. Secondly, this study finds that since the signing of the Paris Agreement, the improvement of enterprise green innovation levels and the alleviation of financing constraints have become important channels for reducing the bankruptcy pressure of carbon venture corporate. This finding offers concrete support for the Porter hypothesis and provides an important practical reference for realizing the green transformation of enterprises. Thirdly, this paper explores the diverse impacts of carbon risk on bankruptcy pressure across varying company sizes, property rights, and industry competition intensities. In addition to providing a more comprehensive view of the economic consequences associated with carbon risk, this study also offers theoretical guidance for businesses to customize their strategies in response to environmental regulations.

This study is structured as follows: Section 2 presents a brief overview of relevant literature and introduces our hypothesis. Section 3 outlines the research methodology and data. Section 4 provides a comprehensive analysis of the empirical findings and a range of robustness tests to ensure their validity. Section 5 examines the heterogeneity of the results. Section 6 summarizes the study's results and offers suggestions for further exploration.

2 Theoretical hypothesis

Some scholars believe that carbon risk could alleviate the pressure of corporate bankruptcy to a certain extent. At first, based on the "green transformation" hypothesis, under environmental regulations, the increase in carbon risk can force enterprises to develop low-carbon technologies and improve production efficiency and industry competitiveness, thus enhancing sustainable management ability and proactive green transformation (Porter and Linde, 1995). Meanwhile the external pressure of environmental regulation can prompt enterprises to reflect on their shortcomings in carbon emission reduction and actively seek technological innovation (Ambec and Barla, 2006; Chen et al., 2023; Deng et al., 2024). Secondly, stakeholder theory holds that green transformation by enterprises can promote the achievement of broader social goals, increase the trust between enterprises and stakeholders, and guide enterprises to realize the unity of environmental problem-solving practices and sustainable development goals (Donaldson and Preston, 1995; Gong and Grundy, 2019). In relation to society and the public, enterprises that actively carry out green transformation are more likely to obtain public support. Thirdly, researchers have found that the increase in carbon risk will force companies to improve their management in carbon risk. And actively managing carbon risk helps companies build a positive social image, reducing the spread of negative publicity and the likelihood of public resistance (Bednar, 2012). Through proactive carbon management and environmental initiatives, companies can convey a sense of responsibility and sustainability, enhancing public goodwill and approval (Hartmann et al., 2005; Olsen et al., 2014; Bi et al., 2023). Fourthly, according to the long-term value investment theory, although green innovation may increase enterprise costs in the short term, it has long-term, sustainable investment returns (Pástor et al., 2021), making enterprises that actively carry out green innovation attractive to investors. Investors believe that companies that actively carry out green innovation will obtain higher quantitative investment returns (Edmans, 2011; He et al., 2022).

Based on the analysis above, carbon risk may reduce the bankruptcy pressure of enterprises in the following two ways. Firstly, enterprises enhance their profitability and competitive position through innovation, which then improves their financial status (McGahan and Silverman, 2006). A stronger financial position means that companies face less pressure of going bankrupt. Secondly, enterprises that actively deal with carbon risks and participate in green innovation are more likely to be favored by investors, thereby reducing bankruptcy pressure (Riedl and Smeets, 2017). As a result, therefore this paper propose the following hypothesis.

Hypothesis 1a: The increase in carbon risk could ease the enterprise bankruptcy pressure.

On the contrary, some scholars also indicate that carbon risk would increase the risk of corporate bankruptcy. Firstly, the cost competition hypothesis holds that carbon risk will bring compliance costs to enterprises, causing them to fall into financial difficulties. Previous research has shown that the costs of disclosure, management, and technology upgrades caused by carbon risk may erode the normal production and operation of enterprises, thus having a negative impact on enterprise value (Gorgen et al., 2020; Zhang and Du, 2020; Chen et al., 2023). Particularly asset-heavy businesses typically require significant capital investments to build and maintain assets, and these investments often have long payback cycles. The emergence of carbon risk may lead these enterprises to face dilemmas of asset depreciation and reduced return on investment, harming their financial performance. Secondly, due to the risks associated with carbon emissions and climate change, many investors and financial institutions are beginning to consider low-carbon and climate-friendly investments. Hence, high-carbon industries may face financing pressures, while low-carbon projects and companies may attract more funds (Bolton and Kacperczyk, 2021). Such impacts could lead to short-term increases in production costs and rising financial risks, elevating the risk of bankruptcy for businesses (Jung et al., 2018).

Based on the above analysis, carbon risk may affect the bankruptcy pressure of corporates by increasing the cost, expenditure, and uncertainty of the cash flow of enterprises, thus increasing their bankruptcy pressure (Ilhan et al., 2021; Giglio et al., 2021). As a result, this paper propose the following hypothesis.

Hypothesis 1b: Carbon risk is positively correlated with corporate bankruptcy pressure.

3 Data collection and model building

3.1 Data collection and processing

This study selects listed companies in Shanghai and Shenzhen A-shares from 2011 to 2021 as the sample. Companies engaged in the following industries are defined as high carbon emission enterprises: oil and gas extraction, electricity, heat, and gas production and supply, metal products manufacturing, petroleum processing, coking and nuclear fuel processing, ferrous metal smelting and rolling, chemical raw materials and chemical products manufacturing, non-ferrous metal smelting and rolling, chemical fiber manufacturing, non-metallic mineral products manufacturing, housing construction, non-ferrous metal mining, civil engineering construction, metal products machinery and equipment repair, construction decoration and other construction industries, non-metallic mineral mining, paper and paper products manufacturing, and wood processing and wood, bamboo, rattan, palm, and straw products manufacturing. Other companies in addition to the above companies are classified as low carbon emission enterprises.

Based on this classification, the sample was further screened as follows: (1) exclusion of ST, SST, and *ST companies; (2) exclusion of the financial and real estate industries; (3) exclusion of samples with significant missing values. Ultimately, 24,956 observations were obtained in this study. To avoid the effect of extreme values, all continuous variables are winsorized at the one percent level. In this study, companies from carbon-intensive industries are designated as the experimental group, while the remaining companies serve as the control group. All data utilized in the analysis are sourced from the CSMAR database and the CNRDS database.

3.2 Specification of the model

To empirically assess the impact of carbon risk on corporate bankruptcy pressure, this study employs a DID model, a methodology commonly utilized in research to examine policy effects (Drysdale and Hendricks, 2018; Dewaelheyns et al., 2023; Cheng et al., 2024). The setup of the model is shown in Equation 1 below:

$$\text{Insolvency}_{i,t} = \beta_0 + \beta_1 Carbon_i{}^{*}Post_t + \beta_2 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

where, $Insolvency_{i,t}$ stands for the Z-score of firm *i* in year *t*; *Carbon* is a dummy variable that indicates whether the enterprise is a high-carbon enterprise, and *Post* is a binary variable indicating the year *t* of the signing of the Paris Agreement; $X_{i,t}$ includes a set of control variables; μ_i refers to individual fixed effects; λ_t represents year fixed effects; and $\varepsilon_{i,t}$ denotes stochastic disturbances affecting corporate bankruptcy pressure. β_1 is the most concerned estimated coefficient in this study, reflecting the influence of carbon risk on corporate bankruptcy pressure.

3.3 Selection of variables

3.3.1 Explained variable

Bankruptcy pressure. The Altman Z-Score (Altman, 1968) is employed as the measure for bankruptcy pressure in this study. The Altman Z-Score is widely recognized for its accuracy and is considered one of the more reliable models for predicting a company's financial stress and health (Almamy et al., 2016). The formula used to calculate the Z-score is shown in Equation 2 below:

TABLE 1 Variable definitions.

Variable type	Name	Symbol	Definition or measurement method
Dependent variable	Bankruptcy risk	Insolvency	Use Z-score as the standard for measuring bankruptcy risk
Independent variable	Grouping variable	Carbon	If the company is in a high-carbon industry, the value is 1, otherwise it is 0
	Time variable	Post	The value is 0 before the signing of the Paris Agreement and 1 after the signing
Control variables	The scale of enterprise	Size	Ln (Total assets at the end of the year)
	Top five shareholders' shareholding ratio	Top5	Number of shares held by the top five shareholders/total number of shares
	combined CEO and chairman position	Dual	If the chairman and general manager are the same person, it is 1, otherwise it is 0
	Cashflow ratio	Cashflow	Net cash flow from operating activities divided by total assets
	Return on total assets	ROA	Net profit/total asset balance
	Tangible asset ratio	Tangible	Tangible assets/total assets
	Years listed	ListAge	Ln (current year - year of listing + 1)
Mechanism variables	innovation effect	Patent	Ln (total number of green invention patents + 1)
	financing constraints	SA	SA = −0.737 * Size + 0.043 * Size2 - 0.040 * ListAge

TABLE 2 Descriptive statistics.

Variable	N	Mean	p50	Min	Max	sd
Z-Score	24,954	6.029	3.523	0.128	46.99	7.526
Carbon	24,954	0.234	0	0	1	0.424
Post	24,954	0.642	1	0	1	0.479
Tangible asset ratio	24,954	0.921	0.953	0.0620	1	0.0960
Size	24,954	22.33	22.14	15.58	28.64	1.321
ListAge	24,954	2.293	2.398	0.693	3.466	0.679
Top5	24,954	0.523	0.521	0.00800	0.992	0.152
Dual	24,954	0.262	0	0	1	0.440
Cashflow	24,954	0.0480	0.0460	−0.744	0.876	0.0720
ROA	24,954	0.0380	0.0360	−1.324	0.880	0.0720

$$Z - \text{Score} = 0.6Q_1 + 3.3Q_2 + 1.4Q_3 + 1.2Q_4 + 0.999Q_5 \quad (2)$$

where, Q_1 = the market value of equity/book value of total liabilities ratio; Q_2 = earnings before interest and taxes (EBIT)/total assets ratio; Q_3 = the retained earnings/total assets ratio; Q_4 = the operating capital/total assets ratio; and Q_5 = the revenue/total assets ratio. The Z-score is negatively correlated with the bankruptcy pressure of a company, meaning that the higher the Z-score, the lower the bankruptcy pressure; conversely, the lower the Z-score, the higher the bankruptcy pressure.

3.3.2 Explanatory variable

Carbon × Post. Referring to the research of Nguyen and Phan (2020), we categorize firms as either high-carbon or low-carbon emitters, depending on the emission characteristics of their respective industries. High-carbon companies include those in industries that are considered "carbon intensive" and are the largest emitters of greenhouse gases or consumers of energy. With the tightening of carbon control regulations, heavy emitters are anticipated to face a substantial increase in carbon costs. The individual variable "Carbon" is a dummy variable that measures whether a company belongs to a high-carbon or low-carbon industry. We use the 2012 China Securities Regulatory Commission industry classification to define high-carbon industries. "Post" is a time dummy variable in the DID model that measures exogenous shocks in the Paris Agreement. Given that the Paris Agreement was signed in December 2015, this study assigns a value of 1 for the year 2016 and onwards, and 0 otherwise. The interaction term "Carbon × Post" represents the magnitude of the impact of the Paris Agreement's implementation on the bankruptcy pressure of carbon-intensive corporates before and after its adoption.

TABLE 3 Benchmark regression results.

Variables	(1) Z-Score	(2) Z-Score
Carbon × Post	1.758*** (0.133)	0.854*** (0.123)
Size		−2.073*** (0.106)
ROA		16.95*** (0.862)
Top5		4.288*** (0.513)
Dual		−0.221** (0.106)
Cashflow		2.026*** (0.585)
Tangible asset ratio		4.475*** (0.784)
ListAge		−3.119*** (0.229)
Year FE	YES	YES
Firm FE	YES	YES
Observations	24,954	24,954
R-Squared	0.660	0.703

Note: ***, **, and * indicate the significance of coefficient estimates at the 1%, 5%, and 10% levels, respectively.

3.3.3 Control variables

We also include tangible asset ratio (Tangible), age (List Age), top five customers′ share of revenue (Top 5), Dual, Cashflow, and return on assets (ROA) as company-specific control variables (Gangi et al., 2020). The specific definitions of each variable are shown in Table 1.

3.4 Summary statistics

Table 2 shows descriptive statistics. The mean of the Z-score is 6.029, with a standard deviation of 7.526. The Z-score ranges from 0.128 to 46.992, which indicates that the bankruptcy pressure of the listed companies is highly different. Our Z-score values and those of Ji et al. (2022) are consistent. The mean value of Carbon is 0.234, which signifies that the experimental group accounts for 22.4% of the population, suggesting that most firms have low carbon risk. Summary statistics for other variables generally align with the patterns observed in the existing literature (Pang et al., 2023).

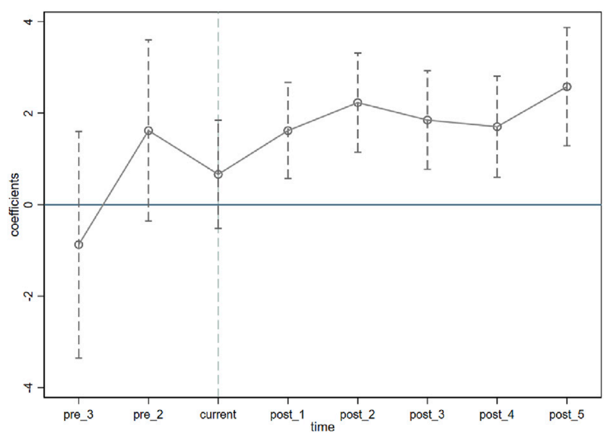

FIGURE 1
Parallel trend test chart.

4 Empirical results

4.1 Baseline result analysis

The implementation of the DID model allowed us to evaluate the impact of carbon risk on the bankruptcy pressure faced by businesses. Table 3 reports the empirical results. In column (1), only the variable Carbon × Post is taken into consideration. In column (2), control variables are introduced to assess the impacts of other factors. Irrespective of the inclusion of control variables, the coefficients associated with the interaction term (Carbon × Post) exhibit significant positive values at the 1% significance level. This suggests a substantial alleviation of bankruptcy pressure following the implementation of the Paris Agreement, thereby supporting Hypothesis 1a.

In terms of control variables, our results are consistent with existing empirical studies that find that Size, Dual, and ListAge can significantly increase the bankruptcy pressure of corporates (Cho et al., 2021; Qin et al., 2023; Dewaelheyns et al., 2023). We also find that ROA and Cashflow can significantly reduce the bankruptcy pressure of corporates, which is consistent with our expectation and existing research. For example, Aziz et al. (2021) observed that enterprises with good performance in ROA and Cashflow have high profitability and low bankruptcy risk. All the other control variables exhibited statistical significance across all specifications, affirming the appropriateness of our selection of control variables.

4.2 Parallel trend test

An important premise for the use of the DID method is that the experimental group and the control group should exhibit a parallel trend before the implementation of the policy; otherwise, the

TABLE 4 Robustness test.

Variables	PSM-DID	DD	Replace the bankruptcy pressure indicator	Change the sample period	Redefine the high-carbon industries
	(1)	(2)	(3)	(4)	(5)
Carbon × Post	0.716*** (0.140)	0.307** (0.142)	−0.265*** (0.040)	0.767*** (0.131)	0.755*** (0.117)
Control variables	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES
Observation	16,165	24,954	24,954	18,526	24,954
R-Squared	0.711	0.322	0.772	0.718	0.703

Note: The t-value is the content in parentheses and is a robust standard error. ***, **, and * indicate the significance of coefficient estimates at the 1%, 5%, and 10% levels, respectively.

estimated results will be biased. Specifically, we created time indicator variables including pre_3, pre_2, pre_1, current, and post_1, post_2, post_3, post_4, post_5. These variables represent 3 years before the implementation of the Paris Agreement, 2 years before, 1 year before, the first year of implementation of the Paris Agreement, the second year, third year, fourth year, and fifth year, respectively. As shown in Figure 1, the middle point in each vertical line is the parameter estimate value, and the two ends are the confidence interval when the confidence level is 95%. Pre_1 as the base year was removed from the regression. The coefficients of the regression terms in the years before the policy shock are not significantly different from zero. The coefficients are significant after the policy was implemented. Hence, the results satisfy the parallel trend test well.

4.3 Test of robustness

We conducted a series of robustness tests to ensure the robustness of the empirical results, which included adopting a PSM-DID method, replacing explanatory variables, changing the sample period, redefining high-carbon industries, and conducing placebo tests. Irrespective of the specific robustness test applied, all the empirical results consistently reinforce the main conclusion of this study.

4.3.1 The PSM-DID method

While the DID method can control some endogeneity problems, it cannot control those caused by “selection bias.” However, PSM-DID can effectively alleviate these problems. Accordingly, this paper uses the PSM-DID model for further analysis. First, all control variables in model (1) were selected as covariables, and a logit model was used to score whether the samples were affected by China’s signing of the Paris Agreement. Second, the 1:1 nearest neighbor matching principle was adopted for non-repeated matching in each year to ensure that samples from different experimental groups would not match the same control group samples. The same or similar scores meant that the two samples had similar characteristics. Finally, model (1) was used for regression analysis of the obtained samples, and the result is presented in column (1) of Table 4. We observe that the coefficient of the interaction term (Carbon × Post) remains significantly positive at the 1% significance level, affirming the robustness of the baseline regression results.

4.3.2 Replace the bankruptcy pressure indicator

In order to ensure the robustness of the research conclusion, we change the measurement method of corporates bankruptcy pressure and carries out benchmark regression again. The initial approach involves utilizing the O-score introduced by Ohlson (1980) as a measurement tool, the calculation method is shown in Equation 3:

$$\begin{aligned} O-Score = & -1.43WCTA - 0.521CHIN + \\ & 0.0757CLCA - 1.83FUTL - 0.407SIZE + \\ & 0.285INTWO - 1.72OENEG + 6.03TLTA \\ & -2.37NITA - 1.32 \end{aligned} \tag{3}$$

where, WCTA = Working Capital/Total Assets; CHIN = (NI*t*-NI*t*−1)/(|NI*t*|+|NI*t*−1|), where NI represents net income; CLCA = Current Liabilities/Current Assets; FUTL = Net Operating Cash Flow/Total Liabilities; SIZE = Ln (Total Assets); INTWO = 1 if net income is negative for the past 2 years, otherwise 0; OENEG = 1 if Total Liabilities > Total Assets, otherwise 0; TLTA = Total Liabilities/Total Assets; and NITA = Net Income/ Total Assets. The larger the O-score value, the greater the bankruptcy pressure of the corporates. Secondly, the KMV model is used to measure the bankruptcy pressure of corporates. The specific formula is as follows:

$$DD = \frac{\ln(V/D) + \left(\mu - \sigma_v^2/2\right)T}{\sqrt{T}\sigma_v}$$

where, V is the market value of corporate assets, which is composed of the market value of corporate debt (D) and the market value of equity (E), that is, V = D + E, while the market value of debt (D) is composed of current liabilities and non-current liabilities, that is, current liabilities +0.5 × non-current liabilities. *U* is the expected return on assets, which is assumed to be the stock return of the enterprise in the previous year. Is the volatility of enterprise asset value, which consists of stock volatility and debt volatility, Debt volatility = 0.05 + 0.25 × σ_E, Where σ_E is equity volatility. Further, the volatility of enterprise asset value can be calculated,

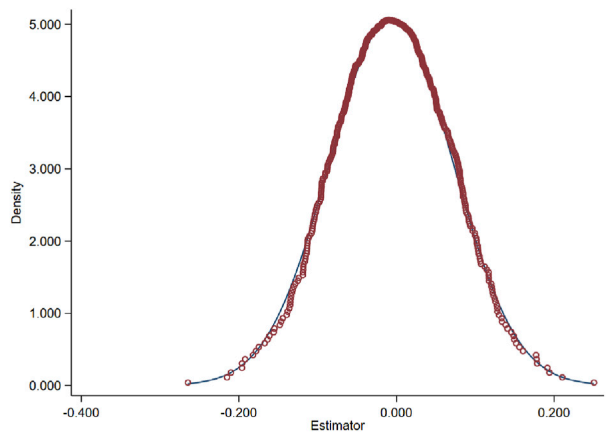

FIGURE 2
Placebo test.

$\sigma_V = \frac{E}{V}\sigma_E + \frac{D}{V}(0.05 + 0.25\sigma_E)$. T is the maturity of the debt, and the maturity time is set to 1 year. By bringing the above calculation formula into the default distance formula, the default distance can be obtained, denoted as DD. The larger the DD value, the smaller the bankruptcy pressure of the corporates. The regression results are shown in column (2) and (3) of Table 4. The findings suggest that carbon risk has notable potential to mitigate firms′ bankruptcy pressure, thus affirming the robustness and credibility of the benchmark outcomes.

4.3.3 Change the sample period

The COVID-19 pandemic had a profound impact on the global economy, causing significant adverse effects on businesses. To assess the influence of carbon risk on corporate bankruptcy pressure without the potential distortions introduced by the pandemic, this study excluded the data for the years 2020 and 2021. The aim was to analyze a more robust and pandemic-free dataset. The results of this analysis are presented in Table 1 column (3). According to the results, after excluding the samples from 2020 to 2021, the coefficient of the core explanatory variable is 0.674. This coefficient is statistically significant at the 1% level and positively significant. This suggests that the main regression results remain robust even after removing the 2020 and 2021 data, indicating that carbon risk continues to have a significant impact on corporate bankruptcy pressure in a pandemic-free context.

4.3.4 Redefine the high-carbon industries

In previous studies, the transportation industry has also been classified as a carbon-intensive industry, but this paper does not include the transportation industry as a high-carbon industry because it has made effective progress in low-carbon technologies in recent years (Wang and Sun, 2021). Therefore, in the robustness test, enterprises in the transportation industry were added as part of the explanatory variables, and the model was regressed again. According to the data presented in column (4) of Table 4, the core explanatory variables continue to display significant positive coefficients, which align with the findings of the baseline regression analysis.

4.3.5 Placebo test

To eliminate the interference of a sample processing effect, this study, referring to Shu et al. (2023), disrupted the order of the explanatory variables, randomly selected some samples, and artificially set the virtual experimental group and virtual control group to construct a new virtual variable and a new interaction term $Carbon^{false} \times Post^{false}$. This variable and term were substituted into the model (1) regression. The simulation experiment was repeated 1,000 times according to the method above. Next, we graph the distribution of the estimated coefficients using the obtained results (see Figure 2).

As shown in Figure 2, the mean value of the estimated coefficients is close to 0 and much smaller than the benchmark regression coefficient (0.860***). This suggests that the observed reduction in bankruptcy pressure in this study is not attributable to random factors.

4.4 Channel analysis

The analysis in this study explores the impact of carbon risk on firm bankruptcy pressure under the Paris Agreement. This section is based on theoretical analysis and aims to reveal the mechanisms through which this impact occurs.

Previous research has found a significant positive relationship between carbon risk and corporate innovation, with environmentally related innovative technologies tending to increase as pollution control costs rise, especially within heavily polluting enterprises (Lanjouw and Mody, 1996; Luo et al., 2023). According to the "green transformation" hypothesis discussed earlier, carbon risk will prompt enterprises to attach importance to technological innovation, optimize management processes, improve production efficiency, obtain competitive advantages and other resources, and reduce pollutant emission (Li, 2014).

Due to the characteristics of carbon emission risks, they pose multiple threats within the commercial environment, and their impact may become pronounced due to constraints on corporate financing. A series of regulations enacted to achieve green transformation are believed to mitigate the information asymmetry problem faced by high-carbon-emitting enterprises in this context (Zhu and Zhang, 2012). With the gradual strengthening of carbon risk, investors are becoming increasingly concerned about a company's environmental performance (Pástor et al., 2021). Therefore, to meet the expectations of the government and investors, high-carbon emission enterprises will likely become more actively involved in information disclosure and carbon emission management to win the favor of investors and government funds.

In the context outlined above, enterprises can reduce bankruptcy pressure in the following two ways. First, through green innovation, they can improve their production efficiency, using green competitive advantages to enhance market share and their business capacity. Second, by disclosing information about their carbon emissions, enterprises can actively obtain the support of government funds and investors, solve the problems of high financing costs, and reduce the pressure of bankruptcy. In other words, enterprises can reduce bankruptcy pressure by increasing green innovation to alleviate financing constraints.

TABLE 5 Channel analysis.

Variables	(1) Financial constraints(SA)	(2) Green innovation
Carbon × Post	−0.009*** (0.002)	0.055*** (0.021)
Control variables	YES	YES
Year FE	YES	YES
Firm FE	YES	YES
R-Squared	0.963	0.701

Note: The t-value is the content in parentheses and is a robust standard error. ***, **, and * indicate the significance of coefficient estimates at the 1%, 5%, and 10% levels, respectively.

TABLE 6 Analysis of heterogeneity.

Variables	Firm size		Corporate ownership		Industry competition intensity	
	(1) Large-scale	(2) Small-scale	(3) SOEs	(4) NSOEs	(5) High-level	(6) Low-level
Carbon × Post	0.290*** (0.069)	1.159*** (0.267)	−0.016 (0.133)	1.549*** (0.197)	1.455*** (0.247)	0.430*** (0.150)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observation	10,791	13,851	9,161	15,720	12,149	12,477
R-Squared	0.821	0.690	0.746	0.687	0.715	0.680

Note: ***, **, and * indicate the significance of coefficient estimates at the 1%, 5%, and 10% levels, respectively.

Referring to Hadlock and Pierce (2010), this paper uses the SA index to measure the financing constraints faced by enterprises. The SA index, which is constructed solely with variables such as company size and company age, which do not significantly change over time, exhibits strong exogeneity. This makes it a suitable proxy for financing constraints as it can help mitigate endogeneity problems. For the measurement of green innovation, this paper follows Jia et al. (2023) in using the natural logarithm of the total number of green invention patents of a company as the proxy variable of green innovation.

Drawing inspiration from Jiang (2022), the Equation 4 is constructed for mechanism testing:

$$M_{i,t} = \theta_0 + \theta_1 Carbon_i {}^* Post_t + \gamma X_{i,t} + u_i + \eta_t + \varepsilon_{it} \quad (4)$$

where, $M_{i,t}$ represents the mechanism variables measuring financing constraints and green innovation, while the remaining items are consistent with model (1).

The empirical results, displayed in column (1) of Table 5, reveal a notable negative coefficient for the SA index, which suggests that carbon risk can mitigate a company's bankruptcy pressure by reducing its financing constraints. The above conclusion is also consistent with previous empirical evidence that carbon risk can mitigate corporates' bankruptcy pressure by easing financing constraints and promoting green innovation (Stamolampros and Symitsi, 2022). The empirical results, as presented in Table 5 column (2), show a significant positive coefficient for green innovation, implying that carbon risk can reduce corporate bankruptcy pressure by promoting green innovation within companies. Comparatively, while studies like those by Porter (1996), Bai and Tian, (2020) suggest innovation offsets regulatory costs, our findings further this by demonstrating how specific types of green innovation contribute to financial stability.

5 Heterogeneity analysis

Carbon risk may have different effects on bankruptcy pressure for different types of businesses. Therefore, this paper carries out heterogeneity tests based on the property rights of the enterprise, the scale of the enterprise, and the degree of competition intensity in the industry in which the enterprise is located.

5.1 Heterogeneity test of firm size

In the process of addressing carbon risk, enterprises of different sizes exhibit starkly different responses (Siedschlag and Yan, 2021). Based on the study of Tian et al. (2020), we establish average-sized companies as the standard and categorize companies into two groups: large-scale enterprises and small-scale enterprises. In Table 6, column (3) represents the regression results for large-scale enterprises, and column (4) represents the regression results for small-scale enterprises. These columns show that carbon risk significantly reduces bankruptcy pressures for small-scale companies, but its impact on large-scale companies is not statistically significant. This may be because although large companies desire to innovate and their R&D investment increases with the size of the company when facing pressure from outside (Wakasugi and Koyata, 1997), the defects in large enterprises' flexibility and information accessibility tend to lead to inefficient innovation activities. This makes enterprise size irrelevant or even negatively correlated with innovation (Rogers, 2004). For small businesses, innovation incentives are more flexible when the businesses are faced with carbon risk, and simple corporate structures allow for more effective collaboration while avoiding bureaucracy (Simonen and mccnn, 2008). Therefore, carbon risk more effectively alleviates corporates bankruptcy pressure among small-scale companies than among large-scale companies.

5.2 Heterogeneity test of property rights

Corporate ownership is a crucial boundary that demarcates different groups of enterprises as firms with diverse ownership structures exhibit significant differences in their cognitive logic, resource endowments, and operational approaches. Consequently, when facing carbon risk, these enterprises may adopt varying strategies. This study delves into the impact of carbon risk on bankruptcy pressures for state-owned enterprises (SOEs) and non-SOEs as differentiated groups. In Table 6, column (1) presents the regression results for non-SOEs, and column (2) presents the regression results for SOEs. These results show that carbon risk significantly reduces bankruptcy pressures for non-SOEs, while its effect on SOE remains insignificant.

This observation can be attributed to several factors. One plausible explanation is that non-SOEs possess a higher degree of flexibility and innovativeness (Wang et al., 2023). Generally, SOEs will inevitably undertake more corporate social responsibility (Liu et al., 2021), while SOEs tend to exhibit lower responsiveness to corporate performance. Conversely, managers in non-SOEs generally face heightened market pressures (Bradshaw et al., 2019), resulting in increased career apprehensions regarding the possibility of corporates bankruptcy. Therefore, non-SOEs are more able to reduce their bankruptcy pressure through green innovation than SOEs are. Moreover, non-SOEs tend to prioritize cost control and efficiency enhancement due to heightened market competition (Tang and Li, 2013). This focus on lean operations drives them to seek energy-efficient and emission-reducing solutions when faced with carbon risk, consequently mitigating carbon-related costs. In summary, the superior adaptive capacity of non-SOEs to mitigate bankruptcy pressures stemming from carbon risk is primarily attributed to their agility and innovation, as well as their emphasis on cost control and efficiency enhancement.

5.3 Heterogeneity test of different industry competition intensity

According to signal theory, intense market competition fosters adversarial relationships among companies (Muhmad et al., 2021). The more intense the market competition, the more competitors are eager to showcase their advantages through various means. Referring to Haushalter et al. (2007), this study adopts the Herfindahl-Hirschman Index (HHI) to measure the intensity of industrial competition. The specific calculation formula is $H_{ij} = \sum (X_{ij}/\sum X_j)^2$, where X_{ij} represents the primary revenue generated by company i within industry j; and $\sum X_j$ is the main business income of all enterprises within industry j. A smaller HHI index means more industry competition intensity. This study analyses the intensity of industry competition in relation to two levels, and divides it into the following two categories according to the median level of industry competition: high-level and low-level industry competition enterprises. In Table 6, column (5) represents the regression results for companies operating in highly competitive industries, and column (6) represents the regression results for companies operating in less competitive industries. In both columns (5) and (6), the coefficients are positive and significant, but the coefficient of enterprises in the industry with high competition intensity is larger, and the result is more obvious. There are several possible reasons for this phenomenon. Regarding the relationship between industry structure and firm characteristics, a highly competitive industry environment forces firms to develop a knowledge base that will enable them to pursue innovation and seize new market opportunities (Weerawardena et al., 2006). In addition, the intensity of industry competition also has a certain promotional effect on the diffusion of enterprise innovation results (Michalakelis et al., 2010). Both conditions make enterprises more inclined to actively respond to carbon risk and implement measures to address potential environmental and market challenges. Therefore, enterprises in highly competitive industries are more likely to proactively deal with the bankruptcy pressure brought about by carbon risk, meaning that carbon risk has a greater impact on enterprises in highly competitive industries.

6 Conclusion and policy implications

Can the increased carbon risk caused by tighter environmental regulations force enterprises to actively implement green transformation and reduce their bankruptcy pressure which is a realistic problem worth exploring. In order to examine this question, this paper employs a based on the Paris Agreement.

In order to investigate the impact of carbon risk on the bankruptcy pressure of enterprises and then to provide the theoretical basis for the sustainable development of enterprises, this paper chooses the Paris climate agreement as a quasi-natural experiment to test the impact and its internal mechanism of carbon risk on corporate bankruptcy pressure which based on DID mode. The results of this paper show that carbon risk can reduce the pressure on enterprises to go bankrupt and high-carbon enterprises reduce their bankruptcy pressure more significantly than the low-carbon enterprises. Furthermore, enterprises primarily mitigate their bankruptcy pressure by engaging in green innovation and alleviating financing constraints, suggesting that both the willingness of enterprises to pursue green innovation and their readiness to disclose carbon risks are enhanced under the pressures associated with carbon risk. The above effect is especially significant for non-SOEs, small-scale enterprises, and companies located in higher competition intensity. Based on the above results, this paper puts forward the following policy recommendations:

Firstly, from a corporate perspective, enterprises should be encouraged to increase investment in R&D while embracing low-carbon technologies. Enterprises engaged in green technology development can effectively curtail carbon emissions, reduce operational costs, and prepare for potential carbon taxes or limitations in the future. Through technological innovation, businesses can also reconfigure their supply chains and foster the development of environmentally friendly products, bolstering their overall resilience and mitigating the impact of carbon risks on bankruptcy susceptibility.

Secondly, governments need to establish a comprehensive system to aid vulnerable enterprises in their green transition. At first, it is essential to establish a carbon risk assessment and monitoring system. Regular assessments and monitoring of carbon risks can help enterprises promptly detect and anticipate potential carbon risk issues, assisting them in formulating mitigation measures. Then the government should provide more carbon reduction technology support, financial subsidies, and tax incentives for small-scale enterprises and SOEs, thereby lowering their carbon reduction costs and risks and enhancing their motivation and capacity for carbon reduction.

Thirdly, carbon risk could effectively reduce the bankruptcy pressure of corporates, but it still needs a system of fund guarantee to ensure the success of corporate low-carbon transitions. The government should institute a carbon financial support program that offers low-interest loans and financing guarantees or subsidies to facilitate carbon reduction investments by enterprises. It can also create or strengthen carbon markets, enabling companies to reduce carbon emissions in cost-effective ways through carbon emission trading, thereby providing additional economic incentives to alleviate funding shortages.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JL: Writing–original draft, Writing–review and editing. ZL: Conceptualization, Data curation, Methodology, Validation, Writing–original draft. TL: Conceptualization, Methodology, Writing–review and editing. YG: Methodology, Visualization, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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