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Climate Policy Uncertainty and Corporate Green Governance: Evidence from China

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Abstract

Drawing on a panel dataset of 27,972 firm-year observations from Chinese A-share listed companies spanning 2009 to 2022, this study employs fixed-effects models to examine the nonlinear relationship between firm-level climate policy uncertainty (FCPU) and corporate green governance expenditure (GGE). The results reveal a robust inverted U-shaped pattern: moderate levels of FCPU encourage firms to increase GGE, while excessive uncertainty discourages it. Financing constraints mediate this relationship; specifically, FCPU exhibits a U-shaped impact on financing constraints, initially easing and then tightening them. Older top management teams accelerate the GGE downturn, while government environmental expenditure delays it, acting as a buffer. Heterogeneity analyses reveal the inverted U-shaped effect is more pronounced for non-polluting firms and state-owned enterprises (SOEs). This study highlights the complex dynamics of FCPU on corporate green behavior, underscoring the importance of climate policy stability and transparency for advancing corporate environmental engagement in China.

Keywords: climate policy uncertainty; corporate green governance; inverted U-shaped relationship; financing constraints; TMT characteristics

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1. Introduction

In recent years, the intensifying threat of global climate change has emerged as one of the most pressing challenges to sustainable development worldwide [1,2]. Characterized primarily by global warming, climate change has led to increasingly frequent and severe extreme weather events, which directly endanger natural ecosystems, disrupt economic activities, and pose serious risks to human health and societal welfare [3]. In response to these challenges, governments across the globe have introduced a wide range of climate-related policies, including carbon pricing mechanisms, emission control regulations, green taxonomies, and climate finance incentives [4]. However, the implementation of these policies often exhibits considerable fluctuations and inconsistencies in terms of regulatory stringency, enforcement pace, target revisions, and policy continuity [5]. As a result, climate policy uncertainty (CPU) has become a salient feature of the institutional environment faced by firms [6,7], influencing their expectations, risk assessments, and strategic behavior—especially in areas involving environmental responsibility and long-term sustainability investments [8].

China is the world's largest emitter of carbon dioxide and a key player in global climate governance. In 2020, the Chinese government announced its "dual carbon" goals—aiming to peak carbon emissions before 2030 and achieve carbon neutrality by 2060 [9].

These long-term targets have marked a significant shift in national development priorities and accelerated the institutionalization of climate policy [10]. Nonetheless, despite the long-term clarity of China's climate vision, firms still operate under a highly dynamic and uncertain policy environment in the short to medium term. Several factors contribute to this uncertainty. First, the inherent complexity of climate governance, including competing policy objectives, evolving regulatory frameworks, and experimental pilot programs, leads to frequent policy adjustments. As China navigates the transition to a low-carbon economy, climate-related policies are often revised to reconcile tensions between environmental goals and economic growth, resulting in shifting compliance requirements and regulatory signals for firms. Second, frequent turnover of local officials, often driven by political cycles and performance evaluation systems, results in discontinuities in local climate policy execution [11,12]. New officials may revise or discontinue the environmental initiatives of their predecessors, adding to the unpredictability of the policy environment for enterprises. As a consequence, firms face difficulties in forming stable expectations about future regulatory intensity, compliance costs, and potential policy incentives [13].

Against this backdrop, firms—acting as micro-level agents of environmental governance—play a vital role in the implementation of climate policy objectives. Their behavioral responses to policy signals directly influence the effectiveness of environmental regulation on the ground. A key manifestation of such responses is corporate green governance expenditure (GGE), which captures firms' capitalized, long-term investments in areas such as pollution control, clean energy infrastructure, and emission reduction facilities. These expenditures reflect the institutional commitment to environmental stewardship and often involve substantial sunk costs with uncertain returns, making them highly sensitive to the stability and credibility of the policy environment [5,8].

When climate policies exhibit instability in timing, content, or enforcement, firms may face strategic ambiguity regarding future regulatory expectations. This study conceptualizes such ambiguity as firm-level climate policy uncertainty (FCPU), which reflects the combined effect of external policy unpredictability and firm-specific exposure to climate-related risks. Unlike general policy uncertainty, FCPU emphasizes a firm's subjective perception of environmental regulation volatility and its relevance to internal green governance decisions.

From a theoretical standpoint, the impact of FCPU on GGE is unlikely to be linear. The existing literature offers contrasting views. On one hand, some studies argue that moderate levels of policy uncertainty can stimulate proactive investment, as firms seek to secure a first-mover advantage or regulatory goodwill in an evolving policy regime [14]. On the other hand, excessive uncertainty may amplify perceived risks, tighten financing constraints, and encourage a defensive "wait-and-see" strategy that delays or reduces green investment commitments [15–17].

This paper seeks to reconcile these divergent perspectives by proposing a nonlinear relationship: when policy uncertainty is moderate, the incentive effect dominates—firms act strategically to adapt early to anticipated regulatory trends [18]. However, as uncertainty escalates, the deterrent effect becomes more salient—firms are less willing to undertake irreversible green investments under conditions of ambiguity and heightened risk [19]. The combined effect yields an inverted U-shaped relationship, wherein GGE first rises with increasing FCPU and subsequently declines beyond a critical threshold.

The main contributions of this study are threefold. First, this paper focuses on green governance expenditure—a key but understudied firm-level variable that directly reflects environmental engagement beyond innovation or disclosure [20]. Second, it adopts a nonlinear analytical framework to explore how FCPU may both promote and inhibit green behavior at different levels, thereby moving beyond the linear assumptions common in

prior studies [21]. Third, it identifies financing constraints as a mediating mechanism that links policy uncertainty to corporate behavior, shedding light on how external institutional risk affects internal resource allocation [22]. Together, these insights provide theoretical and empirical guidance for designing more stable, transparent, and effective climate policy environments that support long-term corporate sustainability investments.

2. Theoretical Framework and Hypothesis Development

In the context of the current green development agenda, corporate green governance expenditure has become a key indicator of firms' environmental responsibility and commitment to sustainable strategies. Fundamentally, such expenditure represents a form of physical investment [23]. While it reflects internal strategic intentions, it is also strongly influenced by the institutional environment shaped by fiscal support and policy guidance from the government [24]. As FCPU rises, firms must contend with the potential cost fluctuations and payoff ambiguities brought about by an unstable institutional environment [25]. The impact of FCPU on green governance expenditure is thus not necessarily unidirectional, but shaped by the interplay between incentive and suppression mechanisms.

To understand firm behavior regarding green governance expenditure under FCPU, it is first necessary to identify the sources of policy uncertainty in China. Although China's long-term climate goals—such as peaking carbon emissions by 2030 and achieving carbon neutrality by 2060—remain stable, the actual implementation process is often accompanied by periodic adjustments, varying regulatory intensity, and regional disparities, all of which increase uncertainty in the institutional environment for firms [26,27]. While the overall direction of green policy has become more stringent, flexibility remains in implementation, including the timing and method of peaking, and the allocation of emission responsibilities across regions and sectors.

On the one hand, there are incentive effects. Industries differ widely in terms of carbon intensity, transition readiness, and technological capacity, making uniform governance standards difficult to enforce [28]. Additionally, disparities in local development levels, industrial composition, and energy structures contribute to uneven enforcement of green governance policies across regions [29]. Some areas have strong administrative capacity and rapidly advancing transitions, while others—especially those dominated by traditional industries—face greater constraints in responding to and implementing green governance, thereby exacerbating uncertainty [30]. At the same time, local governments must balance multiple objectives—economic growth, energy security, and social stability—when implementing green policies [31]. This dynamic balancing act leads to a pattern of phased policy adjustments. For example, during periods of economic stress or external demand contraction, local governments may relax restrictions on high-polluting industries; during recovery or structural upgrading phases, regulatory enforcement may tighten. Therefore, FCPU is not purely disruptive, and it also embodies institutional flexibility and adaptability. From a dynamic policy perspective, moderate uncertainty may signal future regulatory tightening, prompting firms to increase environmental investment to preempt future costs and secure access to policy incentives [32]. This "strategic compliance" behavior is particularly evident when regulatory pressure is moderate and may result in temporary increases in governance expenditure [33]. Moreover, a major source of local policy fluctuation in China is the rotation of local officials [34]. Leadership changes can disrupt previous policy paths, redefine enforcement priorities, and erode institutional continuity [5]. Under China's current official evaluation system, green governance efforts have become an increasingly important indicator of local government performance, particularly as ecological civilization has become a central national objective [35]. In practice, new officials often adjust existing policies to align with their own preferences or performance goals, thereby amplifying FCPU [36]. At

the same time, in order to demonstrate administrative capability and environmental effectiveness within their term, local officials tend to increase regulatory stringency on firms [37]. This creates a top-down pressure mechanism that pushes firms to improve environmental compliance and increase green governance expenditure—especially during the early tenure of newly appointed officials or when policy enforcement tightens [38]. Thus, FCPU can indirectly stimulate corporate green governance through institutional pressure.

On the one hand, there are disincentive effects, and prospect theory suggests that when firms face a highly uncertain external environment, they are more likely to avoid potential losses than to actively pursue uncertain gains [39]. This behavioral bias becomes particularly pronounced under rising FCPU. Green governance expenditure is often characterized by high costs, long investment cycles, and uncertain returns, all of which require stable policy expectations to justify [40]. When FCPU increases, firms face ambiguity regarding policy direction, enforcement intensity, and the durability of incentives, which significantly weakens their willingness to commit to such expenditures [41].

Therefore, the effect of FCPU on green governance is shaped by the tension between incentive and suppression forces, forming a nonlinear, inverted U-shaped relationship. At lower or moderate levels of FCPU, firms may perceive the uncertainty as a signal of imminent regulatory tightening, encouraging early compliance or proactive governance efforts [42]. However, at higher levels of FCPU, uncertainty about institutional risk and future returns becomes dominant, increasing the cost of decision-making and deterring firms from engaging in costly and irreversible environmental investments [19].

The combined result of these mechanisms is that when FCPU remains at low or moderate levels, the incentive effect dominates, and firms are more likely to respond positively. When FCPU becomes excessive, institutional instability begins to outweigh strategic incentives, leading to a decline in green governance expenditure, thus forming an inverted U-shaped trajectory.

Hypothesis 1: *There is an inverted U-shaped relationship between climate policy uncertainty and corporate green governance expenditure.*

In addition, corporate financing constraints may serve as a critical mediating mechanism through which FCPU affects green governance expenditure. Financing constraints refer to the difficulties firms encounter in obtaining sufficient external capital to support their investment activities, particularly in contexts where bank credit is limited or capital market access becomes more restrictive [43,44]. This challenge is especially pronounced for environmental governance expenditures, which typically involve high upfront costs, long payback periods, and complex risk assessments [45]. Such characteristics make these projects particularly vulnerable to capital availability and risk perceptions within the financial system [46].

The relationship between FCPU and corporate financing constraints, however, is unlikely to be monotonic. We propose that this relationship follows a U-shaped pattern, where financing constraints initially decrease with rising FCPU from low to moderate levels, and then increase as FCPU escalates to higher levels.

At low to moderate levels of FCPU, an increase in policy uncertainty may paradoxically ease firms' financing constraints. First, nascent FCPU can act as an early signal of an impending regulatory shift towards a greener economy [14]. Financial institutions, anticipating stricter future environmental standards and the growth of green industries, may proactively seek out and provide more favorable financing terms to firms that demonstrate an early commitment to green transition [47]. These firms are perceived as better positioned to navigate future regulatory landscapes and thus represent lower long-term credit risks [5]. Second, during the initial stages of policy formation, governments might introduce pilot

programs or preliminary green finance incentives (e.g., green credit guidelines, subsidies for green projects) to encourage early adoption [4]. Even with some surrounding uncertainty, these early positive signals can channel financial resources towards environmentally proactive firms, thereby alleviating their financing constraints.

However, as FCPU escalates to high levels, it is expected to significantly tighten firms' financing constraints. First, excessive policy volatility, frequent reversals, or ambiguity in regulatory direction dramatically increase the perceived risk for financial intermediaries [7]. Lenders become more risk-averse when faced with an unpredictable policy environment, as it becomes exceedingly difficult to accurately evaluate the risks and returns associated with green projects. Consequently, financial institutions are likely to tighten credit standards, increase risk premiums, and reduce their exposure to firms operating under high FCPU, especially for long-term, capital-intensive green projects [48]. Moreover, the credibility and effectiveness of any existing policy support mechanisms (e.g., loan guarantees, subsidies) may be eroded under conditions of high overall policy uncertainty. Financial institutions may discount the value of such support if the overarching policy framework is perceived as unstable, thus limiting their willingness to extend credit based on these mechanisms.

Therefore, while moderate FCPU might act as a catalyst improving access to finance for proactive firms, excessive FCPU is likely to trigger risk-averse behavior among financial intermediaries, thereby intensifying firms' financing difficulties and indirectly suppressing green governance expenditure. This leads to our second hypothesis:

Hypothesis 2: *There is a U-shaped relationship between climate policy uncertainty and corporate financing constraints.*

The moderating influence of government environmental expenditure (GEE) on the FCPU-GGE relationship can be profoundly understood through the lens of institutional theory. This theory posits that organizations' strategies are shaped by their need to conform to the rules, norms, and beliefs of their external environment to gain and maintain legitimacy [49]. From this perspective, GEE is not merely a financial input but a powerful institutional signal that communicates the state's commitment and priorities regarding green development [50].

Specifically, high levels of GEE exert both coercive and normative institutional pressures [24]. Coercively, substantial government expenditure signals a credible threat of future, more stringent environmental regulations, incentivizing firms to comply [51]. Normatively, it establishes green investment as a legitimate and socially appropriate corporate behavior, aligning corporate actions with societal values and stakeholder expectations [52,53].

Crucially, this strong institutional signal acts as a stabilizing buffer against the negative effects of policy uncertainty. When the government consistently allocates significant fiscal resources to environmental protection, it confers legitimacy on firms' green projects [54]. This legitimacy reduces the perceived risk associated with these long-term investments, both for the firm's managers and for external stakeholders like investors and lenders [55]. Even if the specifics of a policy fluctuate (high FCPU), the government's clear financial commitment provides an overarching assurance that the general direction towards a green economy is stable. This institutional assurance enhances firms' tolerance for short-term policy volatility [56]. Consequently, in a high-GEE environment, the deterrent effect of uncertainty is weakened, and the turning point at which FCPU begins to inhibit GGE is delayed.

Hypothesis 3: *Increased government environmental expenditure shifts the inverted U-shaped curve between climate policy uncertainty and corporate green governance expenditure to the right.*

While external factors shape the institutional environment, a firm's response is filtered through the cognitive frames of its key decision-makers. By integrating institutional theory with an upper echelons perspective, we can theorize how internal characteristics, such as the average age of the top management team (TMT Age), moderate the firm's reaction to FCPU [57]. Upper echelons theory suggests that executives' personal characteristics, such as age, influence their interpretation of the external environment and subsequent strategic choices [58].

A significant body of recent research indicates that older managers tend to be more risk-averse, exhibit a stronger preference for stability, and are more cautious when making decisions under uncertainty [59,60]. From an institutional perspective, high FCPU represents a state of institutional ambiguity—an environment where the "rules of the game" are unclear, unstable, and unpredictable [42]. This turbulent institutional context directly conflicts with the stability-seeking and risk-averse preferences typically associated with older executives [61].

Therefore, when faced with rising FCPU, the inherent conservatism of older TMT is likely to be amplified. They will perceive the institutional environment as riskier at a lower threshold of uncertainty compared to their younger counterparts [62]. This heightened risk perception will lead them to adopt a "precautionary withdrawal" strategy sooner, reducing or delaying irreversible GEE to shield the organization from potential losses in an unpredictable policy landscape [25]. In this context, the firm's strategic response is driven by a desire to minimize exposure to institutional instability. The negative, deterrent effect of FCPU on GGE will thus manifest earlier and more strongly in firms led by older TMT.

Hypothesis 4: *A higher average age of the top management team shifts the inverted U-shaped curve between climate policy uncertainty and corporate green governance expenditure to the left.*

The theoretical framework of this study is illustrated in Figure 1.

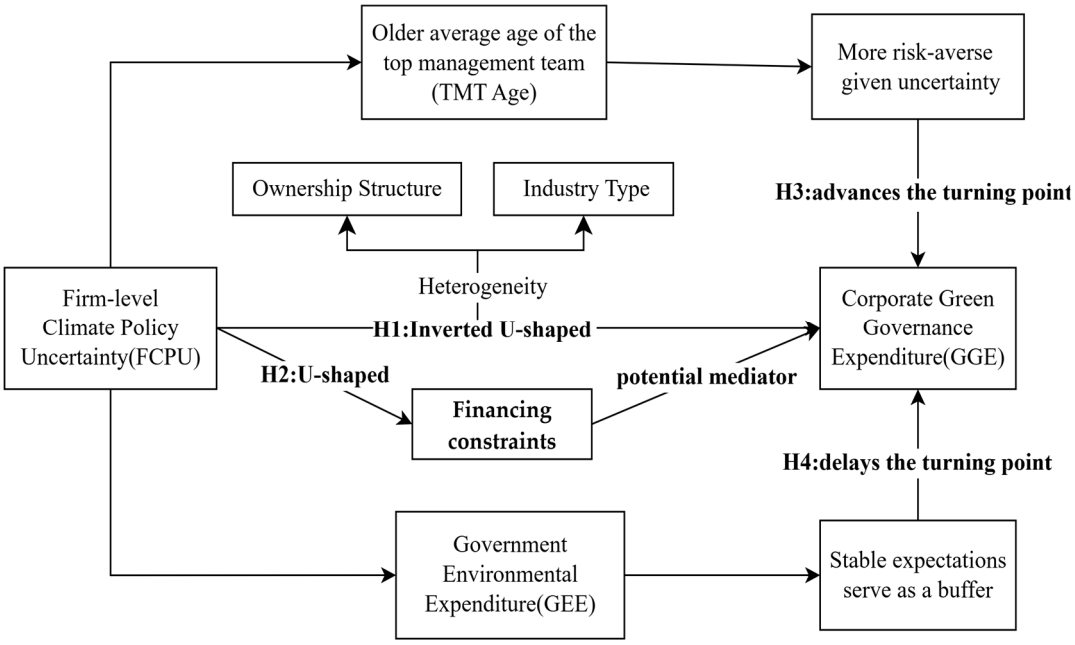


Figure 1. Theoretical framework.

3. Research Design

3.1. Sample Selection

This study uses a panel dataset of Chinese A-share listed companies covering the period from 2009 to 2022. The chosen time frame captures key stages of China's climate policy evolution, beginning with its initial international commitment in 2009 under the Copenhagen Accord, through increasingly ambitious environmental goals outlined in the 12th (2011–2015), 13th (2016–2020), and 14th (2021–2025) Five-Year Plans. The announcement of China's "dual carbon" targets in 2020—aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060—further underscores this period's significance. The frequent policy adjustments and escalating targets during these years provide an ideal context for examining policy uncertainty and its effects on corporate behavior.

Provincial-level climate policy uncertainty data were obtained from the China Climate Policy Uncertainty Index developed by Ma et al. [63]. This index quantifies climate policy uncertainty through textual analysis of climate-related news articles from major Chinese newspapers. Provincial government environmental expenditure data were sourced from the China Statistical Yearbook. Corporate green governance expenditure data were collected from the annual reports. Other firm-level variables were derived from the CSMAR database. To ensure the reliability of our analysis, we excluded ST, *ST, and PT firms, as well as observations with missing key variables. The final dataset comprises 27,972 firm-year observations.

3.2. Variable Definitions

3.2.1. Measurement for Corporate Green Governance Expenditure

Corporate green governance expenditure (GGE) is the dependent variable in this study and reflects a firm's tangible, long-term commitment to environmental governance. Following Song and Dong [64], we define GGE as the total annual expenditure on green governance-related projects recorded under the "construction in progress" account. To ensure the relevance of selected items, we manually reviewed the textual descriptions of all construction projects disclosed in firms' annual reports, identifying those explicitly related to environmental governance practices.

The screening process was implemented using a keyword-matching algorithm that identifies project names containing terms related to environmental protection, waste management, sanitation, soil treatment, forestry, water infrastructure, energy, and other green governance themes. A detailed keyword list is provided in Table A1.

The identified expenditures were aggregated at the firm-year level and scaled by total assets to obtain a comparable measure across firms. This metric captures firm-level strategic investments that contribute to long-term environmental compliance, risk management, and sustainable governance capacity.

3.2.2. Measurement for Firm-Level Climate Policy Uncertainty

Firm-level climate policy uncertainty (FCPU) is the core explanatory variable in this study. Following the methodology of Li et al. [65], we construct a firm-specific climate policy uncertainty indicator by interacting a province-level climate policy uncertainty index with each firm's climate risk disclosure level. This composite measure captures not only the macro-level policy volatility but also the firm's sensitivity to such uncertainty.

Specifically, the provincial-level climate policy uncertainty (CPU) index is obtained from the China Climate Policy Uncertainty Index Database developed by Ma et al. [63]. This index is constructed based on more than 1.7 million articles from six authoritative Chinese newspapers, using the MacBERT deep learning model and a multi-stage auditing and classification process. It captures the intensity and ambiguity of climate policy-related

discourse across provinces, reflecting regional differences in policy uncertainty stemming from economic development disparities and governance heterogeneity.

To account for firms' exposure and response to climate-related risks, we construct a climate risk disclosure index adapted from Wang et al. [13]. Specifically, we develop a dictionary of climate-related keywords and programmatically scan each firm's annual reports to identify the frequency of relevant terms. The raw term frequency is then normalized to generate a standardized index that reflects the firm's strategic attention to, and sensitivity toward, climate risks and opportunities. Details of the index construction are provided in Table A2.

The final FCPU variable is operationalized as the interaction between the provincial CPU index and the firm-level disclosure index. This interaction term captures the extent to which a firm is both affected by external climate policy uncertainty and internally sensitive to such uncertainty through its disclosure and strategic engagement. This approach ensures that the measure reflects heterogeneity across firms and regions, allowing a more nuanced investigation into how climate policy uncertainty translates into firm-level behavioral responses.

3.2.3. Control Variables

To mitigate the influence of other firm-specific and macroeconomic factors on GGE, this paper includes a set of control variables consistent with the recent literature on corporate environmental behavior and policy uncertainty [64–66]. These include Firm Size (Size), Fixed Asset Ratio (FIXED), Largest Shareholder Ownership (Top1), Listing Age (ListAge), Leverage (Lev), Earnings Per Share (EPS), Tobin's Q (TobinQ), Return On Assets (ROA), Cash Flow (Cashflow), and Capital Accumulation Rate (RCA). The definitions for these variables are provided in Table 1.

Table 1. Variable definition.

Variable Name	Symbol	Definition
Corporate Green Governance Expenditure	GGE	Annual sum of environmental/green expenditures in "construction in progress", scaled by total assets. The resulting ratio is multiplied by 100.
Firm-level Climate Policy Uncertainty	FCPU	Interaction of the provincial climate policy uncertainty index and the firm's climate risk disclosure index. This is a unit-less index.
Firm Size	Size	Natural logarithm of the firm's total assets, where assets are measured in Chinese Yuan (CNY).
Fixed Asset Ratio	FIXED	Ratio of fixed assets to total assets.
Largest Shareholder Ownership	Top1	Shares held by the largest shareholder divided by total shares outstanding, expressed as a percentage (%).
Listing Age	ListAge	Natural logarithm of (the number of years since the company's IPO + 1).
Leverage	Lev	Ratio of total liabilities to total assets.
Earnings Per Share	EPS	Net income divided by the weighted average number of common shares outstanding, measured in Chinese Yuan (CNY) per share.
Tobin's Q	TobinQ	Ratio of (market capitalization + total liabilities) to total assets.
Return On Assets	ROA	Ratio of net income to average total assets.
Cash Flow	Cashflow	Ratio of net operating cash flow to total assets.

Table 1. *Cont.*

Variable Name	Symbol	Definition
Capital Accumulation Rate	RCA	Ratio of (Net Capital Expenditures—Depreciation) to beginning total assets.
Average Age of the Top Management Team	TMT Age	The average age of the top management team, measured in years.
Government Environmental Expenditure	GEE	Natural logarithm of annual environmental protection expenditure of each province (in ten thousand yuan) plus 1

3.3. Empirical Models

To formally test the primary hypothesis regarding an inverted U-shaped relationship (H1), this paper specifies the following fixed-effects panel regression model:

$$GGE_{it} = \beta_0 + \beta_1 FCPU_{it} + \beta_2 FCPU_{it}^2 + X_{it'}\gamma + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

where i indexes firms and t indexes years. GGE_{it} represents corporate green governance expenditure. $FCPU_{it}$ denotes firm-level climate policy uncertainty, and $FCPU_{it}^2$ is its quadratic term, included to capture nonlinearity. X_{it} is a vector encompassing the control variables. μ_i signifies firm-specific fixed effects, controlling for time-invariant unobserved heterogeneity across firms. λ_t represents year fixed effects. ϵ_{it} is the idiosyncratic error term.

Hypothesis 1 predicts a statistically significant positive coefficient for β_1 ($\beta_1 > 0$) and a statistically significant negative coefficient for β_2 ($\beta_2 < 0$). Subsequent to estimating Equation (1), this paper employs the U-test procedure developed by Lind and Mehlum [67] to rigorously assess the statistical validity of the inverted U-shape and to estimate the coordinate of the turning point, given by $-\beta_1/(2\beta_2)$.

To investigate the proposed moderating effects (H3 and H4), this paper extends the baseline model (Equation (1)) by incorporating interaction terms between FCPU (and its squared term) and the relevant moderator variable (M_{it}):

$$GGE_{it} = \beta_0 + \beta_1 FCPU_{it} + \beta_2 FCPU_{it}^2 + \beta_3 (FCPU_{it} \times M_{it}) + \beta_4 \left(FCPU_{it}^2 \times M_{it} \right) + \beta_5 M_{it} + X_{it'}\gamma + \mu_i + \lambda_t + \epsilon_{it} \quad (2)$$

where M_{it} is the moderating variables, representing the average age of the top management team (TMT Age) and government environmental expenditure (GEE). $FCPU_{it} \times M_{it}$ denotes the interaction term between FCPU and moderating variables, and $FCPU_{it}^2 \times M_{it}$ is the interaction term between the squared term of FCPU and moderating variables. The others are the same as Equation (1).

4. Empirical Results

4.1. Descriptive Statistics

Table 2 presents the descriptive statistics for the key variables in our study. The mean value of GGE is 8.1963, with a standard deviation of 10.6028, indicating substantial variation in environmental investment levels across the sample firms. FCPU has a mean of 3.9224 and a standard deviation of 2.4124, with a range spanning from 0.00 to 12.66. This wide range suggests considerable heterogeneity in the level of climate policy uncertainty faced by different firms and over the sample period. The descriptive statistics for the control variables are also provided.

Table 2. Summary statistics.

	Count	Mean	sd	Min	Median	Max
GGE	27,972	8.1963	10.6028	0.00	4.23	55.30
FCPU	27,972	3.9224	2.4124	0.00	3.82	12.66
Size	27,972	22.3440	1.3672	19.31	22.10	27.12
FIXED	27,972	0.2158	0.1521	0.00	0.19	0.67
Top1	27,972	34.4611	14.8734	8.48	32.39	74.82
ListAge	27,972	2.0374	0.8086	0.00	2.08	3.50
Lev	27,972	0.4171	0.1986	0.05	0.41	1.00
EPS	27,972	0.4507	0.6462	−1.71	0.32	3.25
TobinQ	27,972	1.9771	1.2234	0.85	1.60	9.51
ROA	27,972	0.0458	0.0619	−0.32	0.04	0.24
Cashflow	27,972	0.0515	0.0672	−0.20	0.05	0.26
RCA	27,972	0.1593	0.3479	−0.36	0.07	2.32

4.2. Baseline Regression Results

Table 3 presents the baseline regression results examining the impact of FCPU on firms' green governance expenditure, with two model specifications reported sequentially. The core explanatory variables are FCPU and its squared term $FCPU^2$, intended to test whether the relationship between FCPU and GGE is nonlinear.

Table 3. Baseline models.

	(1)	(2)
FCPU	0.535 ***	0.419 ***
	(0.123)	(0.125)
FCPU2	−0.054 ***	−0.039 ***
	(0.013)	(0.013)
Size		0.618 *
		(0.350)
FIXED		−40.044 ***
		(2.619)
Top1		0.034
		(0.022)
ListAge		−0.078
		(0.364)
Lev		3.470 ***
		(1.016)
EPS		0.095
		(0.229)
TobinQ		0.131
		(0.081)
ROA		−6.832 ***
		(2.207)
Cashflow		−2.876 *
		(1.457)
RCA		−1.132 ***
		(0.204)
Constant	7.235 ***	0.123
	(0.257)	(8.138)
N	27,972	27,972
Adj.R^2	0.401	0.465
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes: Robust standard errors clustered at province level in parentheses. * $p < 0.10$, *** $p < 0.01$.

Column (1) reports the baseline model, which controls for firm size and year fixed effects, but does not include firm fixed effects. This specification serves to illustrate the initial association between FCPU, $FCPU^2$, and GGE. The results show that the coefficient on FCPU is positive and significant, while the coefficient on $FCPU^2$ is negative and significant, providing preliminary evidence of an inverted U-shaped relationship. Column (2) represents the most comprehensive specification, incorporating both firm fixed effects and year fixed effects, along with all firm-level covariates, thereby improving the rigor of identification.

Across two columns, the coefficient on FCPU remains positive and statistically significant, while the coefficient on $FCPU^2$ remains negative and significant, further confirming a robust inverted U-shaped relationship. Specifically, at low to moderate levels of policy uncertainty, firms may increase their green governance expenditure in anticipation of stricter regulatory enforcement. However, as uncertainty rises beyond a certain threshold, concerns about risk and unpredictable returns may lead firms to delay or reduce their environmental investments. This results in a nonlinear behavioral response, wherein policy uncertainty first promotes and then inhibits corporate green governance efforts.

Although the empirical analysis is based on Chinese listed firms, the results may hold broader relevance for countries with weaker climate performance or underdeveloped regulatory institutions. The observed inverted U-shaped relationship between climate policy uncertainty and green governance expenditure implies that an optimal level of uncertainty may incentivize environmental action, while excessive volatility deters long-term investment. In countries where climate policy is fragmented, frequently revised, or inconsistently enforced, firms may experience even greater difficulty forming stable expectations, resulting in underinvestment in environmental initiatives. These findings highlight the importance of establishing transparent, credible, and forward-looking policy frameworks not only in China but also in other economies seeking to improve climate performance. By improving the consistency and predictability of climate-related regulations, such countries can better motivate corporate actors to contribute to environmental governance and long-term sustainability goals.

Furthermore, this paper formally tests the inverted U-shape using the U-test procedure [67]. The results are reported in the Table 4. The estimated turning point for this relationship occurs at an FCPU level of approximately 5.37 ($=-0.419/(2\times(-0.039))$), which falls well within the observed data range [0, 12.66]. And the test statistics indicate that the slope is significantly positive at the lower bound of the FCPU range and significantly negative at the upper bound, satisfying the conditions for an inverted U-shape (slope at lower bound = 0.419, $p < 0.01$; slope at upper bound = -0.577, $p < 0.01$). The overall test statistic further corroborates the inverted U-shape (t-statistic = 2.67, $p < 0.01$). These findings lend robust support to Hypothesis 1.

Table 4. Results of U-test.

ITEM	STATISTIC	VALUE	T-STAT	*p*-VALUE
Slope at Lower Bound	$\hat{\beta_1} + 2\hat{\beta_2}X_{min}$	0.419	3.360	0.001 ***
Slope at Upper Bound	$\hat{\beta_1} + 2\hat{\beta_2}X_{max}$	−0.577	−2.674	0.006 **
Overall Test	Inverse U-shape	−2.674	2.67	0.006 **
Null Hypothesis (H_0): Relationship is Monotonic or U-shaped				

Notes: ** $p < 0.05$, *** $p < 0.01$.

To visually represent this nonlinear effect, Figure 2 displays the predicted values of GGE across the observed range of FCPU, holding all other covariates at their means. This

plot, generated based on the estimated coefficients from our quadratic model (Column 2, Table 3), effectively illustrates the marginal impact of FCPU on GGE at different levels of FCPU. The graph clearly depicts GGE increasing as FCPU rises from low levels, reaching an estimated peak at the turning point, and subsequently declining with further increases in FCPU. This visualization of the predicted conditional means further corroborates our main finding of an inverted U-shaped relationship.

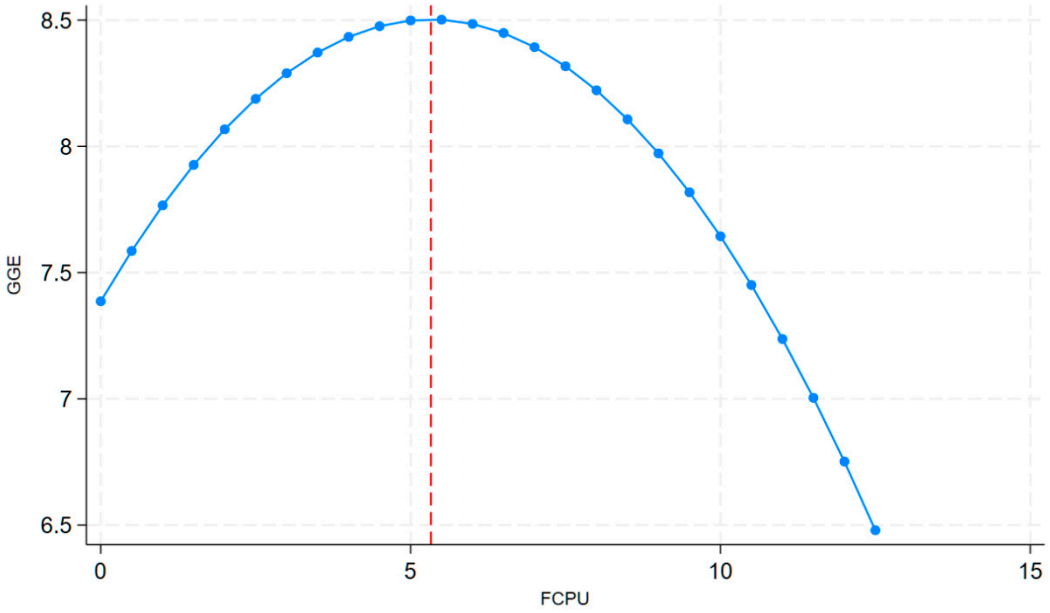


Figure 2. The relationship between FCPU and GGE.

4.3. Robustness Checks

To evaluate the reliability of our baseline findings, this paper conducted a series of robustness checks, with results presented in Tables 5–7.

Table 5. Robustness checks—model specification.

	(1) **Linear**	**(2)** **Linear**	**(3)** **Cubic**	**(4)** **Cubic**
FCPU	0.071	0.078	0.398 **	0.282
	(0.053)	(0.055)	(0.170)	(0.199)
$FCPU^2$			−0.016	−0.001
			(0.043)	(0.046)
$FCPU^3$			−0.003	−0.003
			(0.003)	(0.003)
Constant	7.919 ***	0.286	7.323 ***	0.312
	(0.206)	(8.148)	(0.246)	(8.021)
Controls	No	Yes	No	Yes
N	27,972	27,972	27,972	27,972
Adj.R^2	0.400	0.465	0.401	0.465
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: Robust standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$.

Table 6. Robustness checks—alternative clustering.

	(1) Province-Year	(2) Firm-Year	(3) Firm
FCPU	0.419 ***	0.419 ***	0.419 ***
	(0.126)	(0.121)	(0.110)
FCPU2	−0.039 ***	−0.039 ***	−0.039 ***
	(0.011)	(0.011)	(0.011)
Constant	0.123	0.123	0.123
	(10.163)	(10.367)	(8.139)
Controls	Yes	Yes	Yes
N	27,972	27,972	27,972
Adj.R^2	0.465	0.465	0.465
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes: Robust Standard errors in parentheses. *** $p < 0.01$.

Table 7. Robustness checks—alternative to the fixed effects and the measurement of GGE.

	(1) GGE	(2) GGE	(3) logGGE	(4) logMF
FCPU	0.541 ***	0.726 ***	0.124 ***	0.007 **
	(0.138)	(0.183)	(0.040)	(0.003)
$FCPU^2$	−0.043 ***	−0.035 *	−0.008 **	−0.001 ***
	(0.013)	(0.017)	(0.003)	(0.000)
Constant	−0.650	−0.467	−17.031 ***	3.794 ***
	(3.977)	(2.986)	(1.987)	(0.229)
Controls	Yes	Yes	Yes	Yes
N	27,972	27,972	27,972	26,990
Adj.R^2	0.129	0.074	0.395	0.952
Industry FE	Yes	Yes		
Firm FE			Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: Robust Standard errors in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.3.1. Examining the Model Specification

Table 5 reports the results from alternative model specifications. Columns (1) and (2) present a purely linear model, while Columns (3) and (4) examine a cubic specification by adding the squared and cubic terms of FCPU. Across all four models, the estimated coefficients on FCPU and its higher-order terms are not statistically significant, which strengthens the credibility of the baseline conclusion and the structural robustness of inverted U-shape relationships.

4.3.2. Changing the Clustering Lever

Second, this paper tests the robustness of our standard error estimation by employing alternative clustering methods (Table 6). Clustering standard errors at the province-year level (Column 1), firm-year level (Column 2), or firm level (Column 3) yields qualitatively identical results, with the coefficients for FCPU and $FCPU^2$ remaining statistically significant and retaining their expected signs.

4.3.3. Testing the Robustness of Fixed Effects and the Measurement of GGE

Third, this paper tested the robustness of our estimation by utilizing alternative specifications of the fixed effects and the measurement of our dependent variable (Table 7). Specifically, this paper replaces firm fixed effects with industry and province fixed effects

(Columns 1 and 2). This paper also employs alternative measures for corporate green investment, utilizing the natural logarithm of total environmental investment (Column 3) and the natural logarithm of corporate green management expenses (Column 4). Across all these alternative specifications and measurements, the results consistently support the inverted U-shaped relationship between FCPU and corporate environmental investment, with the coefficients for FCPU and $FCPU^2$ retaining their expected signs and statistical significance.

These tests confirm the resilience of our finding to variations in model setup and variable definition.

4.4. Addressing Endogeneity Concerns

To address potential endogeneity biases arising from omitted variables or reverse causality, this paper employed a two-stage least squares (2SLS) instrumental variable (IV) approach. Following prior studies that use exogenous weather-related variables as instruments for policy or economic conditions [68,69], this paper utilized provincial annual precipitation and its squared term as instruments for FCPU. Precipitation is plausibly exogenous to firm-level green governance decisions but can influence regional policy focus and thus FCPU, particularly in a country like China where water resources and climate adaptation are significant policy concerns [70].

Table 8 presents the IV regression results. The first-stage regression (Column 1) shows that both precipitation and its square are highly significant predictors of FCPU, indicating instrument relevance. The Kleibergen–Paap rk Wald F statistic (21.337) exceeds conventional thresholds for weak instruments, suggesting our instruments possess sufficient strength.

Table 8. IV regression.

	(1) **First Stage (FCPU)**	**(2)** **Second Stage (GGE)**
Precipitation	−1.311 ***	
	(0.177)	
Precipitation2	0.087 ***	
	(0.014)	
FCPU		4.483 **
		(1.954)
FCPU2		−0.329 *
		(0.179)
Constant	1.478 *	
	(0.865)	
Controls	Yes	Yes
N	25,936	25,936
Firm FE	Yes	Yes
Year FE	Yes	Yes
Kleibergen–Paap rk Wald F statistic	21.337	

Notes: Robust Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The second-stage results (Column 2) reveal that the instrumented FCPU variable retains a positive and significant coefficient ($\beta = 4.483$, $p < 0.05$), while the instrumented $FCPU^2$ term remains negative and significant ($\beta = -0.329$, $p < 0.10$). Although the significance level for the squared term is slightly attenuated, the results from the IV regression continue to support the existence of an inverted U-shaped relationship, suggesting our baseline findings are unlikely to be driven solely by endogeneity.

4.5. Heterogeneity Analysis

This paper next explores whether the identified inverted U-shaped relationship varies across different firm types.

Table 9 presents the heterogeneity regression results based on firms' ownership structures, aiming to examine whether FCPU has differential effects on GGE between state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs). Column (1) reports the results for SOEs. The coefficient of FCPU is 0.719, and the coefficient of $FCPU^2$ is −0.062, both statistically significant at the 1% level. These results indicate a clear inverted U-shaped relationship between FCPU and GGE in SOEs. Column (2) shows that for non-SOEs, the estimated coefficients of FCPU and $FCPU^2$ are statistically insignificant. This suggests that changes in FCPU do not significantly influence GGE in these firms. Although the signs of the coefficients for non-state-owned enterprises (non-SOEs) are consistent with an inverted U-shape, they are not statistically significant. This implies that while a theoretical relationship between FCPU and GGE may exist, the actual effect among non-SOEs is too weak or inconsistent to be detected empirically. One likely reason is that non-SOEs typically engage in much lower levels of environmental governance expenditure, which is often discretionary and sensitive to cost considerations. As such, even when policy uncertainty changes, these firms may only make small or uneven adjustments, resulting in little observable impact. Moreover, non-SOEs vary widely in terms of ownership, resources, and sensitivity to regulation, making their responses highly heterogeneous. This diversity further dilutes the average effect, making the overall inverted U-shaped relationship statistically insignificant.

Table 9. Heterogeneity analysis—ownership structure.

	(1) **SOEs**	**(2)** **Non-SOEs**
FCPU	0.719 ***	0.173
	(0.205)	(0.117)
FCPU2	−0.062 ***	−0.018
	(0.020)	(0.011)
Constant	−18.410	13.626
	(11.375)	(12.013)
Controls	Yes	Yes
N	9609	17,276
Adj.R^2	0.513	0.448
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes: Robust standard errors in parentheses. *** $p < 0.01$.

Table 10 presents grouped regression results based on whether firms operate in polluting industries, aiming to examine the heterogeneous effects of FCPU on GGE under different levels of environmental regulatory pressure. Column (1) reports estimates for polluting firms, while Column (2) focuses on non-polluting firms. The key explanatory variables remain FCPU and its squared term, and all models control for firm-specific characteristics, firm fixed effects, and year fixed effects.

In Column (1), the coefficients for FCPU and $FCPU^2$ are 0.363 and −0.036, respectively. Although the signs are consistent with an inverted U-shaped relationship, neither coefficient is statistically significant. This suggests that in polluting industries, FCPU does not have a significant incentive or deterrent effect on GGE. One possible explanation is that polluting firms face rigid compliance requirements due to stricter environmental regulations. As a

result, their green expenditure tends to be more "mandatory" in nature and less sensitive to policy fluctuations, making behavioral adjustments less pronounced in the short term.

Table 10. Heterogeneity analysis—polluting firms.

	(1) **Polluting Firms**	**(2)** **Non-Polluting Firms**
FCPU	0.363	0.309 ***
	(0.292)	(0.098)
FCPU2	−0.036	−0.025 **
	(0.027)	(0.009)
Constant	−20.535	6.705
	(27.926)	(8.218)
Controls	Yes	Yes
N	6287	21,213
Adj.R^2	0.509	0.449
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes: Robust standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$.

In contrast, Column (2) shows that for non-polluting firms, the coefficient on FCPU is 0.309 (significant at the 1% level), and the coefficient on $FCPU^2$ is −0.025 (significant at the 5% level), clearly indicating an inverted U-shaped pattern. This implies that when FCPU is low to moderate, non-polluting firms are more likely to increase GGE in anticipation of future risks or as part of a strategic response. However, when uncertainty rises to a high level, these firms tend to scale back such expenditures due to increased risk aversion. Since these firms face less regulatory pressure, their environmental investments rely more on policy incentives and confidence in the policy environment, making them more susceptible to the nonlinear effects of uncertainty.

Overall, the results suggest that FCPU has a more pronounced and nonlinear effect on GGE for non-polluting firms, forming a typical inverted U-shaped curve. In contrast, the effect is weaker for polluting firms. This finding highlights the importance of designing differentiated regulatory strategies that account for firm characteristics. Policymakers should enhance guidance and policy clarity for non-polluting firms to maintain stable expectations and encourage proactive green behavior. At the same time, more formal enforcement mechanisms should be employed for polluting firms, thereby establishing a dual-track approach to advancing corporate environmental governance.

4.6. Moderating Effects

This paper further investigates the moderating effects of the average age of the top management team (TMT Age) and government environmental expenditure (GEE) using interaction terms as specified in Equation (2). The results are presented in Table 11.

Column (1) of Table 11 presents the moderating role of TMT Age. The coefficient for $FCPU^2 \times$ TMT Age is −0.007, significant at the 1% level, suggesting that as the average age of the management team increases, the inverted U-shaped relationship between FCPU and GGE becomes steeper.

Referring to Haans et al. [21], this paper next examines the moderating effect of TMT Age on the changing of the turning point. The turning point in the moderated model is defined as follows:

$$X^* = \frac{-\beta_1 - \beta_3 M}{2\beta_2 + 2\beta_4 M} \quad (3)$$

To show how the turning point changes as *M* changes, this paper then differentiates X^* with respect to the moderator *M*, which yields the Equation (4):

$$\frac{\delta X^*}{\delta M} = \frac{\beta_1\beta_4 - \beta_2\beta_3}{2(\beta_2 + \beta_4 M)^2} \quad (4)$$

Equation (4) shows that the mathematical condition for this turning point to be independent of M is $\frac{\delta X^*}{\delta M} = 0$, which requires the numerator term $\beta_1\beta_4 - \beta_2\beta_3$ to be zero. The movement of the curve turning point depends on the sign of $\beta_1\beta_4 - \beta_2\beta_3$. If $\beta_1\beta_4 - \beta_2\beta_3 < 0$, the turning point will shift to the left; if $\beta_1\beta_4 - \beta_2\beta_3 > 0$, the turning point will shift to the right.

Table 11. Moderating effect.

	(1) **TMT Age**	**(2)** **GEE**
FCPU	−1.996	4.996 ***
	(1.296)	(1.725)
TMTAge	0.095	
	(0.114)	
FCPU × TMT Age	0.048 *	
	(0.026)	
FCPU2	0.311 **	−0.479 **
	(0.125)	(0.189)
FCPU2 × TMT Age	−0.007 ***	
	(0.003)	
GEE		0.550
		(0.365)
FCPU × GEE		−0.321 ***
		(0.120)
FCPU2 × GEE		0.031 **
		(0.013)
Constant	−2.691	−7.699
	(8.881)	(6.830)
Controls	Yes	Yes
N	27,521	27,521
Adj.R^2	0.464	0.464
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes: Robust standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Thus, following the methods of Haans et al. [21], the calculation of the term $\beta_1\beta_4 - \beta_2\beta_3$ yields a result of −0.0011,indicating that TMT Age shifts the turning point to the left, and consequently, the turning point appears earlier. This may be because older managers tend to be more risk-averse and are more likely to make conservative decisions in response to uncertainty, leading firms to cut green governance investments sooner.

Column (2) of Table 11 shows the moderating effect of government environmental expenditure (GEE). The coefficient for $FCPU^2 \times GEE$ is 0.031, also significant at the 5% level. The calculation result for $\beta_1\beta_4 - \beta_2\beta_3$ is positive, 0.0003. This indicates that GEE plays a right-shifting moderating role on the inverted U-shaped relationship: when public financial support for environmental protection is stronger, firms exhibit greater tolerance for higher levels of policy uncertainty, and the negative turning point occurs later. In other words, robust public environmental investment acts as a buffer, mitigating firms' negative responses under high uncertainty and delaying the decline in GGE.

In summary, both TMT Age and GEE significantly moderate the inverted U-shaped relationship between FCPU and GGE. The former amplifies the suppressive effect of uncertainty, causing the turning point to emerge earlier, while the latter mitigates such effects, shifting the curve rightward and postponing the onset of negative impacts.

4.7. Mediation Analysis

To further explore the potential mediating role of financing constraints in the process by which FCPU affects GGE, this paper measures corporate financing constraints using the SA index and regresses it on FCPU and its squared term to test H2:

$$SA_{it} = \beta_0 + \beta_1 FCPU_{it} + \beta_2 FCPU_{it}^2 + X_{it'}\gamma + \mu_i + \lambda_t + \epsilon_{it} \quad (5)$$

where SA_{it} denotes the SA index, which is a widely used indicator of financing constraints proposed by Hadlock and Pierce [71]. A higher SA value means more severe financing constraints for a firm.

Table 12 presents the results of the mediation analysis, aiming to examine whether financing constraints—measured by the SA index—serve as a mechanism through which FCPU affects GGE. The table reports two regression models, with SA as the dependent variable and FCPU along with its squared term ($FCPU^2$) as the main explanatory variables.

Table 12. Mediation analysis.

	(1) **SA**	**(2)** **SA**
FCPU	−0.000	−0.010 ***
	(0.000)	(0.001)
FCPU2		0.001 ***
		(0.000)
Constant	−4.215 ***	−4.210 ***
	(0.114)	(0.113)
Controls	Yes	Yes
N	27,961	27,961
Adj.R^2	0.963	0.963
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes: Robust standard errors in parentheses. *** $p < 0.01$.

In column (1), the coefficient of FCPU is −0.000 and statistically insignificant, suggesting that without considering nonlinear effects, FCPU does not have a significant linear impact on financing constraints.

In column (2) of Table 12, after including the squared term of FCPU, the coefficient of FCPU becomes −0.010 and is statistically significant at the 1% level, while the coefficient of $FCPU^2$ is 0.001 and significant at the 1% level. This indicates a significant U-shaped relationship between FCPU and financing constraints: moderate levels of FCPU tend to decrease (ease) firms' financing constraints, whereas high levels of uncertainty may lead financial institutions to tighten credit, thereby increasing (tightening) financing pressure for firms.

The nonlinear impact of FCPU on firms' financing conditions ultimately affects their willingness or capacity to invest in environmental governance.

This U-shaped relationship is further illustrated in Figure 3, which plots the predicted SA index across the range of FCPU. The graph clearly shows the SA index decreasing

at lower levels of FCPU, reaching a minimum at the turning point of FCPU, and then increasing as FCPU rises to higher levels, consistent with our Hypothesis 2.

Overall, the findings suggest that financing constraints serve as a potential mediating channel through which FCPU influences GGE.

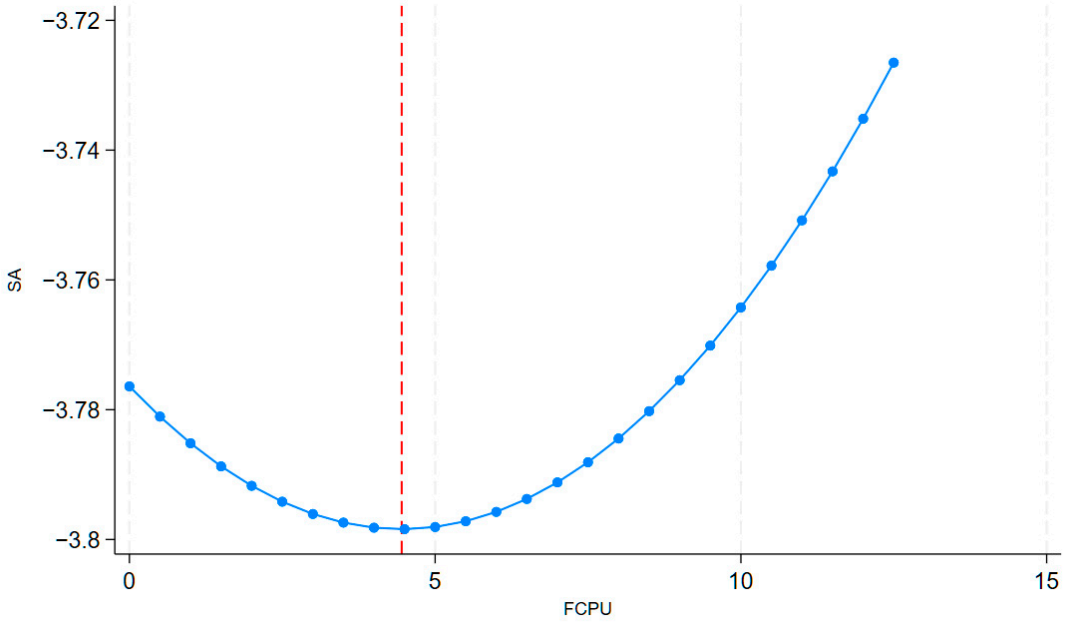


Figure 3. The relationship between FCPU and SA.

5. Conclusions

This paper investigates the nonlinear effects of climate policy uncertainty on firms' green governance expenditure using panel data from Chinese listed companies. This study finds a robust inverted U-shaped relationship: at low to moderate levels, FCPU positively influences firms' environmental governance expenditure, likely as a strategic response to anticipated regulatory tightening; however, when uncertainty rises beyond a certain threshold, the effect becomes negative, as excessive volatility in the policy environment discourages long-term environmental investment. This core finding contributes to the literature on policy uncertainty by highlighting a critical nonlinearity in its impact on specific corporate investments like green governance.

Heterogeneity analyses reveal that this inverted U-shaped relationship is more pronounced in non-polluting firms and state-owned enterprises (SOEs). Conversely, the relationship is less significant for polluting firms and statistically insignificant for non-state-owned enterprises (non-SOEs). Moderation and mediation analyses further show that a higher average age of the top management team (TMT Age) causes the inflection point of the curve to arrive earlier, suggesting that older executives are more risk-averse and adjust investment behavior more quickly in response to uncertainty. In contrast, increased government environmental expenditure shifts the curve to the right, enhancing firms' tolerance for policy uncertainty. Financing constraints are also found to mediate the relationship; FCPU exhibits a U-shaped effect on these constraints (initially easing, then tightening them), which in turn influences firms' green expenditure. This indicates that policy uncertainty indirectly impacts green investment by first improving and subsequently worsening firms' access to capital.

These findings yield important and nuanced policy implications. The inverted U-shaped relationship suggests that the optimal regulatory approach is not the complete elimination of uncertainty, but rather the pursuit of a well-calibrated balance. A moderate level of policy dynamism can be productive; it maintains the salience of environmental

issues on the corporate agenda and encourages a state of proactive engagement as firms prepare for future regulatory shifts. The challenge for policymakers, therefore, is to foster this constructive dynamism while avoiding the excessive volatility that triggers risk aversion and investment paralysis. This can be achieved by clearly distinguishing between long-term strategic stability and short-term policy implementation. Governments must anchor corporate expectations by demonstrating unwavering commitment to long-range goals, such as China's "dual carbon" targets, as this provides a credible and stable horizon for major investments. Within this stable long-term framework, necessary policy adjustments should be implemented transparently and predictably to avoid frequent, disruptive shocks.

Furthermore, our results show that government environmental expenditure acts as a powerful stabilizing force, signaling a credible state commitment that encourages firms to maintain GGE even when faced with policy fluctuations. The heterogeneous responses across firms also call for a differentiated regulatory approach. For non-polluting firms and SOEs, where the effect is most evident, stable incentives are key. For polluting firms, whose expenditure is less sensitive to uncertainty, clear and consistently enforced mandatory standards may be more effective. Finally, given that financing constraints are a key transmission channel, policies should aim to insulate the green finance system from uncertainty shocks by establishing specific, policy-backed tools such as government-guaranteed loan programs or risk-sharing facilities, which can de-risk lending for financial institutions and ensure the continued flow of capital to green projects.

While this study provides robust evidence on the FCPU-GGE nexus, we acknowledge certain limitations that open promising avenues for future inquiry. First, our measurement of GGE, grounded in tangible capital outlays from "construction in progress" accounts, primarily captures long-term investments. Future research could offer a more holistic view by also examining short-term environmental expenditure, such as items within administrative expenses, to differentiate between strategic capital projects and operational greening efforts. Second, to build upon our proxy-based approach and strengthen causal inference, future work could employ quasi-natural experimental designs centered on key policy implementation dates to more precisely identify the causal impact of policy shifts on GGE. Finally, as our findings are situated within China's unique institutional context, extending the analysis to other countries would be invaluable for testing the external validity of the inverted U-shaped relationship and understanding how institutional diversity shapes corporate environmental strategy globally.

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Appendix A

Table A1. Keywords for Identifying Corporate Green Governance Projects.

Keyword Category	Example Keywords	Description
Environmental Protection	"environment", "eco-protection"	General references to environmental and ecological protection.
Waste Management	"waste", "garbage"	Terms related to waste disposal, treatment, or recycling.
Sanitation/Cleaning	"cleaning", "sanitation", "hygiene"	Infrastructure for sanitation, public hygiene, and urban cleaning.
Soil and Land Treatment	"land subsidence", "soil", "land restoration"	Projects addressing soil erosion, land degradation, and treatment.
Forestry and Vegetation	"reforestation", "afforestation", "vegetation"	Forest and vegetation restoration or greening initiatives.
Water Infrastructure	"drainage", "irrigation", "water conservancy", "river"	Construction related to water systems, drainage, and flood prevention.
Disaster Prevention	"flood control", "protective forest", "disaster control"	Projects for natural disaster prevention and ecological barriers.
Energy and Ecology	"energy", "renewable", "green", "ecological"	Energy-efficient, green, or ecologically-focused engineering terms.
Other Related Terms	"environmental assessment", "greening", "parkland"	Other GGE-related keywords not covered above, incl. landscaping and review.

Notes: Keywords are matched using string-based filters in Stata/MP 18.0 based on the project descriptions under the "construction in progress" account. Only those projects explicitly related to environmental governance, infrastructure, or institutional transformation are retained. The final GGE variable is calculated as the total green governance-related project investment in a given year, scaled by total assets.

Table A2. Construction of the Climate Risk Disclosure Index.

Dimension	Item	Description
Disclosure Channel	1. CSR or Sustainability Report	Whether the firm discloses environmental information in a standalone CSR or ESG report.
	2. Annual Report	Whether environmental content appears in the annual report.
	3. Both Channels	Whether both channels are used simultaneously.
Disclosure Content	4. Environmental Governance Structure	Whether the firm discloses internal governance related to environmental issues.
	5. Environmental Policies or Strategies	Disclosure of environmental protection plans or long-term green strategies.
	6. Environmental Objectives or KPIs	Disclosure of environmental targets such as emissions reduction.
	7. Environmental Investments or Expenditures	Whether green capital expenditures are disclosed.
	8. Environmental Performance	Actual performance indicators, such as reduction achievements or audit outcomes.
	9. Pollution Control Measures	Disclosure of specific environmental risk management or control technologies.
	10. Accidents or Violations	Whether the firm reports environmental violations or penalties.
	11. Third-party Verification	Whether environmental disclosures are assured or certified by external agencies.
Disclosure Quantity	12. Number of Environmental Indicators	Whether the firm discloses at least three quantitative environmental indicators.

Table A2. *Cont.*

Dimension	Item	Description
	13. Quantified Pollution Data	Whether pollutant emissions (e.g., SO_2, COD) are disclosed with figures.
	14. Quantified Resource Use Data	Whether energy/water/resource consumption is reported in quantitative terms.

Notes: The total score is calculated by summing all 14 binary indicators. This scoring framework is based on Wang et al. [13] and operationalized via content analysis of company reports, as implemented in the accompanying Stata code you provided. The index reflects not only whether information is disclosed, but also the scope (channels), governance relevance (content), and depth (quantification) of that disclosure.

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