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Hard or Soft Carbon Transparency? Carbon Disclosure and Green Invention Patenting in Chinese Listed Firms

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Abstract

Corporate carbon reporting differs not only in its overall extent but also in the informational content and verifiability of the disclosed items. This study examines the relationship between carbon information disclosure and green invention patenting using 44,327 firm-year observations from Chinese A-share listed firms between 2009 and 2024. Green invention patent applications are used to capture invention-oriented green innovation, while carbon disclosure is decomposed into soft and hard components according to the nature of the underlying disclosure items. The empirical analysis employs firm and year fixed-effects models, standardized coefficient comparisons, cluster bootstrap procedures, ownership interaction tests, and a series of alternative timing, sample, and measurement specifications. The results show that greater lagged carbon information disclosure is positively associated with subsequent green invention patenting. Both soft and hard disclosure are positively associated with green invention patenting, but formal coefficient comparisons indicate that the association is significantly stronger for hard disclosure. Further decomposition shows that governance-, risk-, and strategy-oriented soft disclosure remains positively associated with green invention patenting, whereas carbon-target disclosure alone is not statistically significant. Additional evidence indicates that the hard-disclosure share varies systematically across ownership types, pollution-intensive industries, and provinces. The SA-index results are consistent with a potential financing-constraint channel, although this evidence remains suggestive because the research design is observational and alternative financing-constraint measures do not produce fully consistent results. The positive association between carbon disclosure and green invention patenting is also more pronounced among state-owned enterprises and remains stable across multiple robustness specifications. These findings highlight the importance of disclosure composition and suggest that quantitative, measurable, and externally verifiable carbon information is more strongly associated with green invention patenting than commitment-oriented reporting.



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1. Introduction

Corporate responses to climate change increasingly extend beyond operational emissions management to the disclosure of transition risks, emissions performance, and decarbonization plans [1]. Carbon reporting can reduce informational frictions between

managers and outside stakeholders by making firms' environmental exposure and transition preparedness more visible [2,3]. Evidence from disclosure mandates and voluntary reporting also suggests that carbon information may influence emissions behavior, benchmarking incentives, financing conditions, and market valuation [4–6]. Nevertheless, climate reporting remains uneven in many emerging markets. Firms retain considerable discretion over what they disclose, how specifically they describe their environmental activities, and whether their claims can be independently assessed [5,7]. The central issue is therefore not simply whether firms disclose carbon-related information, but whether different forms of disclosure are associated with different technological responses.

Research on corporate disclosure provides several explanations for why environmental information may be economically relevant. Signaling theory emphasizes that disclosure can convey otherwise unobservable information about managerial priorities and organizational capabilities, although the credibility of a signal depends on its cost and verifiability [8]. Institutional theory, in turn, suggests that firms adjust their reporting practices in response to regulatory expectations, stakeholder pressure, and legitimacy concerns [9]. Empirical studies have linked greater environmental transparency to lower financing costs and stronger corporate valuation [10–12]. A related study shows that environmental innovation is influenced by financial constraints, credit allocation, governance arrangements, managerial experience, and institutional pressure [13–19]. These studies establish important connections among transparency, resource availability, and innovation, but they provide less evidence on whether the informational composition of carbon reporting is associated with invention-oriented green technological activity.

This distinction is important because environmental communication can reflect either substantive organizational action or selective presentation. Firms may emphasize favorable policies, ambitions, and achievements while withholding less favorable environmental information. Greenwashing research shows that such divergence can arise from external pressure, weak monitoring, organizational incentives, and the relatively low cost of making broad environmental claims [20,21]. Selective-disclosure evidence further indicates that the content of environmental reporting responds to scrutiny and institutional norms rather than solely to underlying environmental performance [22]. Consequently, a high aggregate disclosure score does not necessarily imply that the disclosed information is equally informative across firms. Narrative descriptions of governance structures, strategies, risks, and future commitments may communicate managerial orientation, but they are often difficult for external users to verify. By comparison, emissions quantities, carbon intensity, decomposed emissions data, and assured metrics are more directly connected to observable performance.

The measurement of green innovation presents a related challenge. Prior studies commonly use the total number of green patents, although this measure combines technologically demanding invention patents with more incremental utility model patents [23,24]. The distinction is relevant to the broader literature on exploratory and exploitative innovation, which separates the development of novel technological knowledge from the refinement of existing products and processes [25,26]. Recent research also shows that managerial involvement, investor horizons, and institutional incentives shape firms' willingness to undertake exploratory innovation [27,28]. In China, subsidy incentives and political relationships may additionally affect patenting strategies, raising the possibility that increases in patent counts do not always represent comparable technological advances [29,30]. Green invention patent applications therefore provide a more focused indicator of invention-oriented green activity than aggregate green patent counts. They do not, however, directly reveal patent novelty, citation impact, commercialization, or environmental effectiveness. The interpretation adopted in this study is correspondingly narrower: green invention

applications capture a more technologically demanding form of green patenting, rather than a complete measure of innovation quality.

Against this background, the paper distinguishes between soft and hard carbon disclosure. Soft disclosure covers climate governance, risk identification, strategic orientation, and forward-looking environmental commitments. Hard disclosure is centered on emissions-related metrics, carbon intensity, emissions decomposition, value-chain information, and verification-oriented items. The classification does not assume that soft information is necessarily symbolic or that every hard item is entirely quantitative. Instead, it reflects differences in the extent to which disclosure is linked to measurable performance and can be evaluated by outside stakeholders. This approach is consistent with the broader objective of climate-reporting frameworks to improve the comparability and decision usefulness of firms' climate-related risks, opportunities, and performance indicators [31]. It also permits an empirical assessment of whether reporting content matters beyond the total amount of information disclosed.

Financing conditions may provide one explanation for the relationship between carbon reporting and green invention activity. Invention-oriented environmental projects require sustained expenditure, involve uncertain technological outcomes, and often generate returns only after an extended development period. Firms subject to greater financing constraints may therefore be less able to maintain these investments [13–15]. More informative carbon disclosure may reduce uncertainty surrounding environmental strategy and transition exposure, thereby improving the information available to external capital providers. Research on reporting regulation and financial disclosure further indicates that transparency can influence firms' innovation incentives and access to resources [32,33]. In this study, financing constraints are examined as a potential explanatory channel rather than treated as definitively identified causal mediation.

The empirical analysis draws on 44,327 firm-year observations for Chinese A-share listed companies from 2009 to 2024. China provides a useful setting because carbon reporting developed alongside substantial variation in local environmental regulation, industrial transition pressure, ownership structure, and corporate green patenting. The analysis first examines the association between lagged carbon disclosure and subsequent green invention patent applications. It then decomposes the disclosure index into soft and hard components and formally compares their standardized coefficients. Additional tests separate carbon targets from the remaining soft items, examine disclosure composition across ownership types, pollution-intensive industries, and provinces, and evaluate whether the main estimates remain stable after accounting for recent sample years and industry-year and province-year shocks. Financing constraints and state ownership are considered as supplementary channel and heterogeneity analyses.

The study contributes to the literature in three respects. First, it shifts attention from aggregate carbon reporting to the composition of disclosed information. The item-level classification and supplementary validation tests show that hard and soft disclosure represent empirically distinct reporting practices rather than an arbitrary division of the total index. Second, the study relates carbon disclosure to green invention patenting instead of relying only on total green patent output. This approach provides more specific evidence on invention-oriented environmental activity while recognizing the limitations of patent applications as measures of technological importance. Third, the findings clarify the boundary between commitment-oriented climate communication and reporting that is more closely tied to measurable carbon performance. Hard disclosure exhibits a stronger association with subsequent green invention patenting, while the evidence on financing constraints is interpreted more cautiously as an exploratory channel. The results therefore emphasize the

informational content of climate reporting without extending the interpretation beyond what the observational research design can establish.

2. Theoretical Background and Hypothesis Development

2.1. Carbon Disclosure and Green Invention Patenting

Carbon information disclosure can shape how external stakeholders assess a firm's environmental exposure, transition preparedness, and capacity to respond to climate-related risks. In the presence of information asymmetry, outside investors and creditors may find it difficult to distinguish firms that have incorporated low-carbon objectives into their operations from those that rely primarily on general environmental claims. More informative carbon reporting can reduce this uncertainty by making environmental priorities, governance arrangements, and emissions-related activities more visible to capital providers and other stakeholders [2,3,8,10].

Institutional pressures provide a complementary explanation for the relevance of carbon disclosure. Firms operate under regulatory expectations, market scrutiny, and broader social demands for environmental accountability. These pressures may encourage firms to formalize climate responsibilities, improve internal monitoring, and align their reporting practices with external expectations [9,11,19]. Carbon disclosure may therefore reflect not only communication with external audiences but also the development of organizational routines for identifying emissions sources, evaluating climate risks, and coordinating low-carbon activities.

The preparation of carbon information may also have internal implications for technological decision-making. Measuring emissions, reviewing energy use, and documenting transition strategies can reveal inefficiencies and technological constraints that might otherwise remain dispersed across business units. Reporting regulation and financial disclosure have been shown to affect firms' innovation incentives and resource allocation decisions [32,33], while organizational capabilities and supply-chain integration can support the development of environmentally oriented products and processes [34]. Carbon disclosure may consequently be associated with subsequent green invention activity through both external information effects and internal learning processes.

This study focuses on green invention patent applications rather than aggregate green patent counts. Total green patent measures combine invention patents with utility model patents, although the two categories may differ in technological requirements and innovative content [23,24]. The distinction is also consistent with research separating exploratory innovation from incremental refinement of existing technologies [25,26]. Managerial involvement, investor horizons, subsidies, and political incentives may affect firms' willingness to pursue technologically demanding projects and their incentives to accumulate patents for strategic purposes [27–30]. Green invention patenting therefore provides a more focused indicator of invention-oriented environmental activity, although it does not directly measure patent citations, novelty, commercialization, or environmental effectiveness.

Taken together, these arguments suggest that firms providing more extensive carbon information are more likely to exhibit greater subsequent green invention activity. Because the research design does not exploit exogenous variation in disclosure, the expected relationship is formulated as an association rather than a causal effect.

Hypothesis 1 (H1). *Carbon information disclosure is positively associated with subsequent green invention patenting.*

2.2. Disclosure Credibility and the Hard–Soft Distinction

The informational relevance of carbon disclosure depends not only on how much information is reported but also on whether external users can evaluate the underlying claims. Signaling theory suggests that a signal is more informative when it is sufficiently specific, costly to imitate, and open to external verification [8,35]. Broad statements of environmental commitment may communicate managerial priorities, but their credibility is difficult to assess when they are not accompanied by observable indicators or evidence of implementation.

This issue is central to the literature on greenwashing and selective environmental disclosure. Firms may emphasize favorable environmental policies, objectives, or achievements while providing less information about unfavorable outcomes or implementation failures. Such reporting choices can arise when the legitimacy benefits of environmental communication exceed the expected costs of external scrutiny [20,21]. Evidence on selective disclosure further shows that the scope and content of environmental reporting vary with stakeholder attention, institutional norms, and monitoring intensity [22]. The informational value of a disclosure score may therefore depend on the relative weight assigned to narrative commitments and measurable performance indicators.

In this study, soft carbon disclosure consists of information concerning climate governance, risk and opportunity management, strategic orientation, and carbon-related targets. These items can be useful because they reveal how climate issues are incorporated into organizational responsibilities and forward-looking plans. Soft disclosure should not, however, be treated as necessarily equivalent to symbolic reporting. Governance arrangements and risk-management information may reflect substantive managerial attention, even when they are not expressed through emissions quantities.

Hard carbon disclosure is more closely oriented toward emissions metrics, carbon intensity, emissions decomposition, value-chain information, and verification-related items. Such information is generally more readily compared across firms and over time and can be assessed against subsequent operating performance. Climate-reporting frameworks similarly emphasize the decision usefulness of measurable risks, opportunities, and performance indicators [31]. Although some metrics-related items may contain qualitative elements, their underlying subject matter is more directly connected to observable carbon performance than general strategic narratives or prospective commitments.

The distinction is particularly relevant for carbon reduction targets. A quantitative target may appear precise but remains forward-looking until the firm reports progress, realized emissions, or independent verification. Target disclosure can therefore communicate ambition without necessarily demonstrating implementation. By separating target-oriented disclosure from governance-, risk-, and strategy-related soft information, the empirical analysis examines whether the stronger association of hard disclosure is driven merely by the classification of targets.

Hard disclosure may exhibit a stronger relationship with green invention patenting for several reasons. First, measurable emissions information enables external stakeholders to compare reported commitments with realized outcomes. Second, quantitative indicators expose inconsistencies between environmental claims and operational performance to greater regulatory and market scrutiny. Third, the production of granular emissions data may require more developed internal monitoring and information systems, which can also support the identification of technological inefficiencies. Carbon performance evaluation may consequently influence firms' green technology decisions and investment priorities [36].

Accordingly, both disclosure components may contain relevant information, but hard disclosure is expected to have a stronger association with subsequent invention-oriented

green activity because it is more closely connected to measurable performance and external accountability.

Hypothesis 2 (H2). *Hard carbon disclosure has a stronger positive association with subsequent green invention patenting than soft carbon disclosure.*

2.3. Financing Constraints as a Potential Explanatory Channel

Green invention projects typically require sustained expenditure, involve uncertain technical outcomes, and generate returns only after lengthy development and commercialization periods. Firms facing tighter financing constraints may therefore be less able to maintain these projects, particularly when external financiers cannot readily evaluate the economic value and environmental relevance of green R&D activities [13,14]. Credit allocation and financing conditions have also been shown to influence firms' environmental innovation decisions [15].

Carbon disclosure may be related to financing conditions by improving the information available to investors and creditors. More detailed reporting can make a firm's environmental exposure, governance arrangements, and transition strategy easier to assess. Carbon transparency has been associated with a lower cost of capital [10], while broader evidence suggests that reporting regulation and financial disclosure can influence firms' access to resources and innovation decisions [32,33]. Where outside capital providers regard carbon information as credible, greater disclosure may be associated with lower perceived uncertainty and improved financing conditions.

Reduced financing pressure may, in turn, allow firms to sustain long-horizon green R&D expenditure. Greater financial flexibility can help firms absorb project failure risk, retain specialized technical personnel, and continue investment before commercial returns become available. Institutional investors and other long-term capital providers may also influence firms' capacity to undertake innovation with delayed payoffs [37,38].

These arguments motivate an examination of financing constraints as a possible channel linking carbon disclosure to green invention patenting. However, the financing measure used in this study is an indirect index rather than a direct measure of credit availability or financing prices. Moreover, the panel design does not isolate exogenous changes in financing conditions. Financing constraints are therefore treated as an exploratory explanatory channel rather than as a separately identified causal mechanism. The corresponding empirical results are interpreted as evidence consistent with this channel, not as definitive proof of mediation.

Based on the preceding arguments, Figure 1 summarizes the two hypothesized relationships and the exploratory financing-constraint channel examined in the empirical analysis.

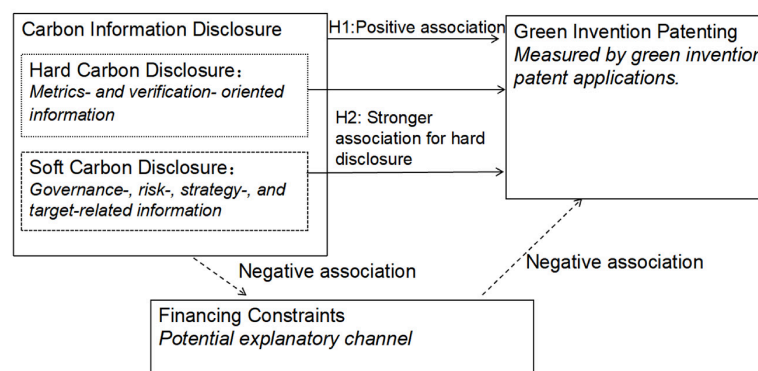


Figure 1. Conceptual framework and hypothesized associations. Notes: The solid paths represent the two hypotheses examined in this study. H1 proposes a positive association between carbon information

disclosure and subsequent green invention patenting. H2 proposes that hard disclosure has a stronger association with green invention patenting than soft disclosure. The dashed paths represent financing constraints as a potential explanatory channel examined through supplementary analysis and do not imply separately identified causal mediation.

3. Research Design

3.1. Sample Selection and Data Sources

The empirical analysis combines carbon disclosure and firm-level accounting and governance information from the China Stock Market and Accounting Research database (CSMAR) with green patent records from the China Research Data Services Platform (CNRDS). The CSMAR data were extracted in August 2025, while the CNRDS patent data were extracted in November 2025. The original control-variable dataset contains 59,300 firm-year observations covering 2006–2024. Restricting the source data to 2008–2024 removes 2912 observations. The year 2008 is retained exclusively to construct the lagged disclosure measures, while the baseline estimation period covers 2009–2024.

The sample-screening procedure excludes 1275 financial-sector observations because financial firms operate under distinct balance-sheet structures and regulatory arrangements. A further 1980 firm-year observations designated as ST, *ST, or PT in the relevant fiscal year are removed to limit the influence of abnormal financial and operating conditions. These restrictions yield 53,133 eligible firm-year observations representing 5515 listed firms.

The eligible observations are matched with the carbon disclosure and green patent datasets by stock code and fiscal year. A total of 1077 observations cannot be matched across the three data sources, producing an initial merged panel of 52,056 firm-year observations. A subsequent validation check identifies one observation with an out-of-range carbon-governance component, which is removed before reconstructing the disclosure indices. The validated merged panel therefore contains 52,055 firm-year observations.

Of these observations, 1293 from 2008 are used only to construct the lagged variables and are not included in the baseline regressions. All lagged variables are generated using strict consecutive calendar-year lags, meaning that a lagged value is assigned only when the immediately preceding fiscal year is observed for the same firm. During the 2009–2024 estimation period, 6107 observations lack either a valid consecutive-year lag or at least one variable required by the baseline specification. This screening leaves 44,655 complete firm-year observations. The firm fixed-effects estimator subsequently removes 328 singleton observations that do not contribute to within-firm identification. The final baseline sample therefore consists of 44,327 firm-year observations from 4973 firms. Appendix A Table A1 summarizes the sample-construction procedure.

Continuous accounting variables are winsorized at the 1st and 99th percentiles. Patent applications are assigned to their filing years. Although the CNRDS patent data were extracted in November 2025 and include application records through 2024, observations near the end of the sample may be less mature than earlier records. This concern is more pronounced for patent grants because examination and authorization occur with a delay. Accordingly, the grant-based specification is re-estimated after excluding 2023 and 2024. The application-based models are also repeated after excluding 2024 and, separately, 2023–2024 to assess whether the main findings depend on late-period observations.

3.2. Variable Measurement

3.2.1. Dependent Variable: Green Invention Patenting

The primary outcome is green invention patenting. GreenInv is defined as the natural logarithm of one plus the number of green invention patent applications filed by firm i in year t :

$$GreenInv_{i,t} = \ln(1 + Green\ Invention\ Patent\ Applications_{i,t}).$$

Green invention applications provide a more focused indicator of invention-oriented environmental activity than aggregate green patent counts because they exclude utility model patents, which generally involve more incremental technological modifications. Nevertheless, applications do not directly measure patent novelty, citation influence, commercialization, or realized environmental performance. The variable is therefore interpreted as an indicator of green invention activity rather than a complete measure of technological quality.

Two alternative outcomes are used in the robustness analysis. GreenApp is the natural logarithm of one plus total green patent applications, while GreenInvGrant is the natural logarithm of one plus granted green invention patents. Because grant decisions occur after an examination period, the grant-based model is also estimated after removing the last two sample years.

3.2.2. Independent Variable: Carbon Information Disclosure

Carbon disclosure is measured using the CSMAR Carbon Information Disclosure Index. The index assigns scores to disclosure items covering climate governance, risks and opportunities, low-carbon strategy, carbon targets, emissions metrics, emissions decomposition, value-chain information, and verification-related content. Its theoretical range is 0–50, with a higher value indicating broader coverage and greater comprehensiveness of carbon-related reporting.

The main explanatory variable, L1_CID, is the one-year-lagged value of the aggregate disclosure score:

$$L1_CID_{i,t} = CID_{i,t} - 1$$

Lagging the disclosure variable establishes a temporal sequence in which reporting precedes the observed patent outcome. It does not, however, eliminate omitted time-varying factors or establish a causal effect.

3.2.3. Soft and Hard Carbon Information Disclosure

The aggregate disclosure score is decomposed according to the underlying content and temporal orientation of the index items. The classification is theory-driven rather than derived from the regression results. The complete item-level mapping, scoring rules, and category assignments are reported in Appendix A Table A2.

SoftCID combines disclosure concerning climate governance, risks and opportunities, low-carbon strategy, and carbon-related targets:

$$SoftCID = Governance + RiskOpportunities + Strategy + Targets.$$

These items primarily describe organizational arrangements, managerial orientation, risk-management processes, and forward-looking commitments. To examine whether the treatment of target disclosure affects the results, the analysis further separates SoftCID into SoftCore and Targets. SoftCore contains governance, risk and opportunity, and strategy items, while Targets captures carbon objectives, mitigation commitments, and transition progress.

HardCID comprises metrics- and verification-oriented items:

$$HardCID = EmissionsIndicators + DecompositionIndicators + ValueSupplyIndicators + OtherIndicators.$$

These items relate to emissions quantities, carbon intensity, disaggregated emissions information, value-chain and supply-chain reporting, and verification-related content. The classification does not imply that every hard-item observation is fully quantitative or that

every soft item is merely symbolic. Rather, hard items concern information that is generally more closely connected to measurable carbon performance and external assessment.

The regression analysis uses one-year-lagged values of the disclosure components. Because the original soft and hard indices have different ranges, standardized versions are used for formal coefficient comparisons. The null hypothesis that the standardized coefficients are equal is evaluated using an F-test. An additional specification jointly includes standardized SoftCore, Targets, and HardCID.

HardShare is defined as

$HardShare = \frac{HardCID}{CID}$, and is calculated only when $CID > 0$. Appendix A Table A3 compares this disclosure composition across ownership types, pollution intensity, broad regions, and provinces.

3.2.4. Financing-Constraint Measure

Financing constraints are proxied by SA_abs, the absolute value of the SA index. A larger value indicates stronger financing constraints. The measure is used to examine whether the empirical results are consistent with a possible financing-constraint channel linking carbon disclosure to green invention patenting.

The SA index is an indirect proxy derived primarily from firm size and age rather than a direct measure of credit availability or financing prices. The sensitivity analysis therefore excludes Size and FirmAge from the financing-constraint equation, restricts the estimation to a common financing-index sample, and compares the SA results with the WW, FC, and KZ indices. The results are interpreted as exploratory channel evidence rather than causal mediation.

3.2.5. Control Variables

The regressions include accounting, governance, audit, and ownership characteristics that may covary with firms' carbon reporting and patenting decisions. These controls are firm size (Size), leverage (Lev), return on assets (ROA), revenue growth (Growth), operating cash flow (CashFlow), board size (Board), board independence (Indep), CEO duality (Dual), firm age (FirmAge), Big4 audit affiliation (Big4), and state ownership (SOE). Their operational definitions are reported in Table 1.

3.3. Model Specification

The baseline specification relates current green invention patenting to carbon information disclosure in the preceding year:

$$GreenInv_{i,t} = \alpha + \beta_1 L1_CID_{i,t} + \gamma' X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}, \quad (1)$$

where $GreenInv_{i,t}$ is the natural logarithm of one plus the number of green invention patent applications filed by firm i in year t . $L1_CID_{i,t}$ denotes the one-year-lagged aggregate carbon disclosure score and is equivalent to $CID_{i,t-1}$. $X_{i,t}$ represents the vector of firm-level control variables defined in Table 1. Firm fixed effects, μ_i , absorb time-invariant firm characteristics, while year fixed effects, λ_t , capture macroeconomic, regulatory, and policy shocks common to firms in a given year. Standard errors are clustered at the firm level to account for heteroskedasticity and within-firm serial correlation.

The coefficient β_1 is interpreted as the conditional association between carbon disclosure in the preceding year and subsequent green invention patenting. Although the lagged specification improves temporal ordering, it does not eliminate omitted time-varying determinants or establish a causal effect.

Table 1. Variable Definitions and Measurement.

Variable	Symbol	Measurement
Outcome variables		
Green invention patenting	GreenInv	$\ln(1 + \text{number of green invention patent applications filed by firm (i) in year (t)})$
Total green patenting	GreenApp	$\ln(1 + \text{total number of green patent applications})$
Granted green inventions	GreenInvGrant	$\ln(1 + \text{number of granted green invention patents})$
Future green invention patenting	F1_GreenInv	One-year lead of GreenInv, requiring consecutive firm-year observations
Lagged green invention patenting	L1_GreenInv	One-year lag of GreenInv
Carbon disclosure variables		
Carbon information disclosure	CID	Aggregate CSMAR carbon disclosure score covering climate governance, risks and opportunities, strategy, targets, emissions metrics, emissions decomposition, value- and supply-chain information, and other carbon-related items; theoretical range: 0–50
Lagged carbon disclosure	L1_CID	$(CID_{i,t-1})$
Logarithmic carbon disclosure	L1_ln_CID	$(\ln(1 + CID_{i,t-1}))$
High carbon disclosure	HighCID	1 if L1_CID exceeds the annual sample median; 0 otherwise
Two-year-lagged carbon disclosure	L2_CID	$(CID_{\{i, t-2\}})$
Disclosure-composition variables		
Soft carbon disclosure	SoftCID	Sum of climate governance, risks and opportunities, low-carbon strategy, and carbon-target disclosure scores
Lagged soft disclosure	L1_SoftCID	$(SoftCID_{i,t-1})$
Core soft disclosure	SoftCore	Sum of climate governance, risks and opportunities, and low-carbon strategy disclosure scores
Lagged core soft disclosure	L1_SoftCore	$(SoftCore_{i,t-1})$
Carbon-target disclosure	Targets	Score assigned to carbon objectives, mitigation commitments, and transition-progress items
Lagged target disclosure	L1_Targets	$(Targets_{i,t-1})$
Hard carbon disclosure	HardCID	Sum of emissions indicators, emissions-decomposition items, value- and supply-chain indicators, and other metrics- or verification-oriented items
Lagged hard disclosure	L1_HardCID	$(HardCID_{i,t-1})$

Table 1. Cont.

Variable	Symbol	Measurement
Standardized disclosure components	z_L1_SoftCID, z_L1_HardCID, z_L1_SoftCore, z_L1_Targets	Standardized values of the corresponding lagged disclosure measures, with mean zero and standard deviation one in the relevant estimation sample
Hard-disclosure share	HardShare	(HardCID/CID), calculated only for observations with (CID > 0)
Financing-constraint variables		
SA-based financing constraints	SA_abs	Absolute value of the SA index; a higher value indicates stronger financing constraints
Standardized SA index	z_SA_abs	Standardized value of SA_abs in the common financing-index sample
Alternative financing-constraint indices	z_WW, z_FC, z_KZ	Standardized WW, FC, and KZ indices used in the common-sample sensitivity analysis
Control variables		
Firm size	Size	Natural logarithm of total assets
Leverage	Lev	Total liabilities/total assets
Profitability	ROA	Net profit/total assets
Firm growth	Growth	Annual growth rate of operating revenue
Operating cash flow	CashFlow	Operating cash flow ratio
Board size	Board	Natural logarithm of the number of directors
Board independence	Indep	Independent directors/total board members
CEO duality	Dual	1 if the chief executive officer also serves as board chair; 0 otherwise
Firm age	FirmAge	Natural logarithm of firm age
Big4 audit affiliation	Big4	1 if the financial statements are audited by a Big4 accounting firm; 0 otherwise
State ownership	SOE	1 for state-owned enterprises; 0 otherwise
Supplementary grouping variables		
Pollution-intensive industry	Pollute	1 if the firm operates in a pollution-intensive industry; 0 otherwise
Eastern region	East	1 if the registered province is classified as eastern China; 0 otherwise
Central region	Mid	1 if the registered province is classified as central China; 0 otherwise
Western region	West	1 if the registered province is classified as western China; 0 otherwise

To examine whether the informational composition of carbon reporting is related differently to green invention patenting, the aggregate disclosure index is decomposed into soft and hard components:

$$GreenInv_{i,t} = \alpha + \beta_1 L1_SoftCID_{i,t} + \beta_2 L1_HardCID_{i,t} + \gamma'X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}. \quad (2)$$

Here, $L1_SoftCID_{i,t}$ and $L1_HardCID_{i,t}$ denote the one-year-lagged soft and hard carbon disclosure measures, respectively. Because the two indices have different theoretical ranges and empirical dispersions, their unstandardized coefficients are not directly comparable. Equation (2) is therefore also estimated using standardized disclosure variables. Hypothesis 2 is evaluated through a formal coefficient-equality test:

$$H0: \beta_1 = \beta_2.$$

Rejection of the null hypothesis, together with a larger standardized coefficient for hard disclosure, would indicate that metrics- and verification-oriented reporting has a stronger conditional association with subsequent green invention patenting than soft disclosure.

A supplementary classification specification separates carbon-related targets from the remaining soft disclosure items:

$$GreenInv_{i,t} = \alpha + \beta_1 zL1_SoftCore_{i,t} + \beta_2 zL1_Targets_{i,t} + \beta_3 zL1_HardCID_{i,t} + \gamma'X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}. \quad (3)$$

In Equation (3), $zL1_SoftCore_{i,t}$ captures standardized lagged disclosure concerning climate governance, risks and opportunities, and low-carbon strategy. $zL1_Targets_{i,t}$ represents standardized lagged carbon-target disclosure, while $zL1_HardCID_{i,t}$ represents standardized lagged hard disclosure. This specification evaluates whether the stronger association of hard disclosure is attributable to the treatment of target-oriented items within the original soft disclosure category.

Financing constraints are examined as a potential explanatory channel rather than as a separately identified causal mechanism. The first channel equation relates lagged carbon disclosure to the SA-based financing-constraint proxy:

$$SA_abs_{i,t} = \alpha + \theta_1 L1_CID_{i,t} + \gamma'X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}, \quad (4)$$

where $SA_abs_{i,t}$ is the absolute value of the SA index. A higher value indicates stronger financing constraints. A negative estimate of θ_1 would indicate that greater lagged carbon disclosure is conditionally associated with lower SA-based financing constraints.

The second channel equation includes both lagged carbon disclosure and the financing-constraint proxy in the green invention patenting model:

$$GreenInv_{i,t} = \alpha + \delta_1 L1_CID_{i,t} + \delta_2 SA_abs_{i,t} + \gamma'X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}. \quad (5)$$

A negative estimate of δ_2 , combined with a negative estimate of θ_1 , would produce a positive estimated coefficient product, $\theta_1 \delta_2$. The statistical uncertainty surrounding this product is evaluated using firm-level cluster bootstrap procedures.

Because the SA index is an indirect proxy rather than a direct measure of credit availability, financing prices, or borrowing volume, a statistically significant product term is interpreted only as evidence consistent with a potential financing-constraint channel. It is not treated as proof of causal mediation. The interpretation is further evaluated through specifications excluding Size and FirmAge, a common financing-index sample, alternative financing-constraint measures, and a model relating current financing constraints to next-year green invention patenting.

4. Research Results

4.1. Descriptive Statistics

Table 2 presents descriptive statistics for the final baseline sample of 44,327 firm-year observations. GreenInv has a mean of 0.641 and a median of zero, indicating that green invention patenting is concentrated among a subset of listed firms. The corresponding means of GreenApp and GreenInvGrant are 0.917 and 0.336, respectively. The higher mean of total green patent applications reflects the inclusion of both invention and utility model patents, whereas the lower grant measure is consistent with the examination process preceding patent authorization.

Table 2. Descriptive Statistics.

Variable	N	Mean	SD	Min	Median	Max
GreenInv	44,327	0.641	1.046	0.000	0.000	7.217
GreenApp	44,327	0.917	1.230	0.000	0.000	7.466
GreenInvGrant	44,327	0.336	0.742	0.000	0.000	6.718
L1_CID	44,327	10.876	9.103	0.000	9.000	49.000
L1_SoftCID	44,327	7.883	5.482	0.000	7.000	22.000
L1_HardCID	44,327	2.993	4.174	0.000	1.000	28.000
SA_abs	44,327	3.865	0.268	2.974	3.862	4.698
Size	44,327	22.266	1.290	19.415	22.069	26.452
Lev	44,327	0.426	0.204	0.028	0.420	0.910
ROA	44,327	0.031	0.067	−0.556	0.033	0.222
Growth	44,327	0.143	0.408	−0.673	0.087	5.076
CashFlow	44,327	0.047	0.068	−0.222	0.046	0.282
Board	44,327	2.116	0.199	1.609	2.197	2.708
Indep	44,327	0.377	0.054	0.250	0.364	0.600
Dual	44,327	0.296	0.456	0.000	0.000	1.000
FirmAge	44,327	2.969	0.339	0.693	2.996	4.304
Big4	44,327	0.062	0.242	0.000	0.000	1.000
SOE	44,327	0.337	0.473	0.000	0.000	1.000

Note: This table reports descriptive statistics for the final baseline regression sample. GreenInv, GreenApp, and GreenInvGrant are measured as the natural logarithm of one plus the corresponding green patent counts. L1_CID, L1_SoftCID, and L1_HardCID are constructed using strict consecutive calendar-year lags. SA_abs denotes the absolute value of the SA financing-constraint index.

Lagged carbon disclosure also varies substantially across firms. L1_CID has a mean of 10.876, a standard deviation of 9.103, and an observed range from zero to 49. The mean of L1_SoftCID is 7.883, compared with 2.993 for L1_HardCID. Soft disclosure is therefore considerably more prevalent than metrics- and verification-oriented hard disclosure, although the relatively large dispersion of both measures indicates substantial cross-firm heterogeneity in reporting practices.

SA_abs has a mean of 3.865 and a standard deviation of 0.268. Among the indicator variables, approximately 29.6% of the observations involve CEO duality, 6.2% involve Big4 auditors, and 33.7% correspond to state-owned enterprises. Overall, the descriptive statistics show that green invention patenting is unevenly distributed and that firms differ substantially in the extent and composition of carbon disclosure.

4.2. Correlation Analysis and Multicollinearity Test

Table 3 reports the Pearson correlation coefficients and variance inflation factors based on the same 44,327 firm-year observations used in the baseline regressions. GreenInv is positively correlated with L1_CID, L1_SoftCID, and L1_HardCID, with correlation coefficients of 0.348, 0.341, and 0.312, respectively. These unconditional correlations indicate that firms providing more extensive carbon disclosure also tend to exhibit greater green invention

patenting. However, the correlations do not account for unobserved firm heterogeneity, common annual shocks, or other firm-level characteristics and therefore should not be interpreted as tests of H1 or H2.

L1_CID is strongly correlated with L1_SoftCID and L1_HardCID, with coefficients of 0.957 and 0.924, respectively. These high correlations are expected because the aggregate disclosure index is constructed as the sum of its soft and hard components. Accordingly, L1_CID is not included in the same regression specification as L1_SoftCID and L1_HardCID. The correlation between L1_SoftCID and L1_HardCID is 0.773, indicating that firms providing more extensive governance-, strategy-, and commitment-oriented information also tend to report more metrics- and verification-oriented carbon information.

SA_abs is negatively correlated with GreenInv but positively correlated with L1_CID, with coefficients of -0.032 and 0.137 , respectively. The positive unconditional correlation between L1_CID and SA_abs differs from the negative coefficient obtained in the fixed-effects channel analysis. This difference does not necessarily indicate inconsistent findings because the Pearson correlation combines cross-sectional differences, common time trends, and within-firm variation, whereas the fixed-effects model estimates the conditional relationship from within-firm changes after accounting for year effects and observed firm characteristics. Appendix A Table A4, Panel A shows that the coefficient of L1_CID becomes negative after year fixed effects are introduced and remains negative after firm-level controls and firm fixed effects are added. The sign reversal is therefore consistent with common time patterns and cross-sectional differences influencing the unconditional correlation.

The correlation between SA_abs and FirmAge is relatively high at 0.895, which is expected because firm age is an input in the construction of the SA index. The corresponding VIF values are 5.64 for SA_abs and 5.85 for FirmAge, while the mean VIF is 2.20. Although these results do not indicate severe multicollinearity across the model as a whole, the values for SA_abs and FirmAge point to meaningful overlap between the financing-constraint proxy and its underlying firm characteristics. The financing-constraint analysis therefore includes an additional specification excluding Size and FirmAge. The estimated coefficient of L1_CID remains substantively unchanged in that specification, reducing concern that the result is mechanically driven by overlapping variable construction.

Overall, the correlation matrix does not reveal problematic relationships among the main disclosure components once the aggregate disclosure index is excluded from the component-based regressions.

4.3. Baseline Regression Results

Table 4 presents the baseline firm fixed-effects estimates. All specifications include firm and year fixed effects, and standard errors are clustered at the firm level. The dependent variable is GreenInv, defined as the natural logarithm of one plus the number of green invention patent applications. All disclosure variables are constructed using strict consecutive calendar-year lags. Accordingly, the coefficients are interpreted as conditional associations rather than causal effects.

Table 3. Pearson Correlations and Variance Inflation Factors.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	VIF
(1) GreenInv	1.000																—
(2) L1_CID	0.348 ***	1.000															—
(3) L1_SoftCID	0.341 ***	0.957 ***	1.000														2.64
(4) L1_HardCID	0.312 ***	0.924 ***	0.773 ***	1.000													2.56
(5) SA_abs	−0.032 ***	0.137 ***	0.129 ***	0.130 ***	1.000												5.64
(6) Size	0.443 ***	0.407 ***	0.406 ***	0.354 ***	0.052 ***	1.000											2.00
(7) Lev	0.177 ***	0.125 ***	0.132 ***	0.100 ***	0.068 ***	0.474 ***	1.000										1.60
(8) ROA	0.009 *	−0.001	0.004	−0.006	−0.079 ***	0.046 ***	−0.322 ***	1.000									1.47
(9) Growth	−0.001	−0.075 ***	−0.070 ***	−0.071 ***	−0.078 ***	0.034 ***	0.035 ***	0.231 ***	1.000								1.09
(10) CashFlow	0.016 ***	0.068 ***	0.068 ***	0.058 ***	0.000	0.075 ***	−0.160 ***	0.408 ***	0.028 ***	1.000							1.22
(11) Board	0.076 ***	0.067 ***	0.081 ***	0.038 ***	−0.015 ***	0.254 ***	0.145 ***	0.046 ***	0.006	0.044 ***	1.000						1.66
(12) Indep	0.026 ***	0.012 **	0.001	0.025 ***	−0.031 ***	−0.005	−0.018 ***	−0.026 ***	−0.002	−0.014 ***	−0.544 ***	1.000					1.48
(13) Dual	−0.026 ***	−0.042 ***	−0.057 ***	−0.017 ***	−0.059 ***	−0.169 ***	−0.133 ***	−0.001	0.012 ***	−0.015 ***	−0.197 ***	0.123 ***	1.000				1.13
(14) FirmAge	0.082 ***	0.218 ***	0.201 ***	0.212 ***	0.895 ***	0.194 ***	0.135 ***	−0.097 ***	−0.090 ***	0.007	0.009 *	−0.008 *	−0.068 ***	1.000			5.85
(15) Big4	0.169 ***	0.192 ***	0.176 ***	0.187 ***	−0.098 ***	0.332 ***	0.088 ***	0.045 ***	−0.003	0.074 ***	0.093 ***	0.032 ***	−0.051 ***	0.009 **	1.000		1.18
(16) SOE	0.127 ***	0.112 ***	0.132 ***	0.071 ***	0.063 ***	0.334 ***	0.265 ***	−0.027 ***	−0.044 ***	0.005	0.289 ***	−0.078 ***	−0.311 ***	0.113 ***	0.121 ***	1.000	1.30

Note: This table reports Pearson correlation coefficients and variance inflation factors based on the 44,327 firm-year observations used in the baseline regressions. All correlations are calculated using the same complete estimation sample. The VIFs are obtained from an auxiliary OLS regression including L1_SoftCID, L1_HardCID, SA_abs, and the full set of firm-level control variables. Firm and year fixed-effect indicators are not included in the VIF calculation. L1_CID is excluded from the VIF specification because it is constructed as the sum of L1_SoftCID and L1_HardCID. The mean VIF is 2.20. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4. Carbon Disclosure and Green Invention Patenting.

Variables	(1) GreenInv	(2) GreenInv	(3) GreenInv	(4) GreenInv
L1_CID	0.0103 *** (0.0009)			
L1_SoftCID		0.0045 *** (0.0015)		
L1_HardCID		0.0175 *** (0.0021)		
z_L1_SoftCID			0.0246 *** (0.0085)	
z_L1_SoftCore				0.0429 *** (0.0077)
z_L1_Targets				−0.0053 (0.0070)
z_L1_HardCID			0.0731 *** (0.0088)	0.0701 *** (0.0089)
Size	0.2991 *** (0.0176)	0.2994 *** (0.0176)	0.2994 *** (0.0176)	0.2967 *** (0.0175)
Lev	−0.1367 *** (0.0503)	−0.1360 *** (0.0502)	−0.1360 *** (0.0502)	−0.1338 *** (0.0501)
ROA	0.1050 (0.0729)	0.1000 (0.0730)	0.1000 (0.0730)	0.0945 (0.0729)
Growth	−0.0204 *** (0.0077)	−0.0202 *** (0.0077)	−0.0202 *** (0.0077)	−0.0194 ** (0.0077)
CashFlow	−0.0509 (0.0590)	−0.0505 (0.0589)	−0.0505 (0.0589)	−0.0523 (0.0588)
Board	−0.0239 (0.0567)	−0.0270 (0.0567)	−0.0270 (0.0567)	−0.0248 (0.0565)
Indep	0.0748 (0.1696)	0.0692 (0.1696)	0.0692 (0.1696)	0.0715 (0.1692)
Dual	0.0364 ** (0.0152)	0.0357 ** (0.0152)	0.0357 ** (0.0152)	0.0363 ** (0.0152)
FirmAge	0.0710 (0.1183)	0.0738 (0.1181)	0.0738 (0.1181)	0.0757 (0.1179)
Big4	−0.0974 (0.0613)	−0.0989 (0.0610)	−0.0989 (0.0610)	−0.1003 (0.0611)
SOE	0.0117 (0.0353)	0.0147 (0.0352)	0.0147 (0.0352)	0.0144 (0.0352)
Observations	44,327	44,327	44,327	44,327
Number of firms	4973	4973	4973	4973
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Adjusted R-squared	0.7021	0.7024	0.7024	0.7027
Within R-squared	0.0576	0.0585	0.0585	0.0596
F-test: z_L1_SoftCID = z_L1_HardCID			10.24	
p-value			0.0014	
F-test: z_L1_SoftCore = z_L1_HardCID				4.13
p-value				0.0421

Note: This table reports firm fixed-effects regression results. The dependent variable is GreenInv, measured as the natural logarithm of one plus the number of green invention patent applications. Column (1) examines aggregate carbon disclosure. Column (2) decomposes the aggregate index into its soft and hard components. Column (3) uses standardized soft and hard disclosure measures to compare their relative associations with green invention patenting. For the standardized disclosure variables, a one-unit increase represents a one-standard-deviation increase in the corresponding disclosure measure. Because GreenInv is measured as the natural logarithm of one plus the number of green invention patent applications, $\exp(\beta) - 1$ represents the estimated percentage change in one plus the application count associated with a one-unit increase in the explanatory variable. Column (4) further separates carbon-target disclosure from governance-, risk-, and strategy-oriented soft disclosure. All lagged variables are constructed using strict consecutive calendar-year observations. Equality tests for the standardized coefficients are conducted using firm-clustered covariance estimates. All specifications include the baseline control variables, firm fixed effects, and year fixed effects. Firm-clustered robust standard errors are reported in parentheses. **, and *** indicate statistical significance at the 5%, and 1% levels, respectively.

Column (1) examines the aggregate carbon disclosure index. The coefficient of L1_CID is 0.0103 and is statistically significant at the 1% level, indicating that more extensive carbon disclosure in the preceding year is positively associated with subsequent green invention patenting. Because GreenInv is measured as the natural logarithm of one plus the number of green invention patent applications, the coefficient implies that a one-point increase in lagged aggregate carbon disclosure is associated with an approximately 1.04% increase in one plus the number of green invention patent applications, holding the control variables and fixed effects constant. Using the sample standard deviation of L1_CID reported in Table 2, which is 9.103, a one-standard-deviation increase in aggregate carbon disclosure corresponds to a 0.0938-log-point increase in GreenInv, equivalent to an approximately 9.83% increase in one plus the application count. These percentage interpretations refer to one plus the number of applications rather than directly to the raw application count. This result supports H1.

Column (2) decomposes the aggregate disclosure index into its soft and hard components. The coefficients of $L1_SoftCID$ and $L1_HardCID$ are 0.0045 and 0.0175, respectively, and both are statistically significant at the 1% level. Because the two components differ in their theoretical ranges and empirical dispersion, Column (3) uses standardized measures to facilitate a formal comparison. The coefficient of $z_L1_SoftCID$ is 0.0246, whereas that of $z_L1_HardCID$ is 0.0731. As the disclosure variables in Column (3) are standardized, these coefficients represent the estimated change in $GreenInv$ associated with a one-standard-deviation increase in each disclosure component. A one-standard-deviation increase in lagged soft disclosure is associated with a 0.0246-log-point increase in $GreenInv$, equivalent to an approximately 2.49% increase in one plus the number of green invention patent applications. The corresponding estimate for hard disclosure is 0.0731 log points, equivalent to an approximately 7.58% increase in one plus the application count. The estimated magnitude for hard disclosure is therefore approximately three times that for soft disclosure. The equality test rejects the null hypothesis that the two coefficients are equal ($F = 10.24$, $p = 0.0014$), indicating that hard carbon disclosure has a significantly stronger association with subsequent green invention patenting than soft carbon disclosure. Thus, the difference between the two disclosure components is evident in both statistical significance and estimated economic magnitude.

Column (4) further separates carbon-target disclosure from the remaining soft-disclosure items. The coefficient of $z_L1_SoftCore$, which captures climate governance, risks and opportunities, and low-carbon strategy, remains positive and statistically significant. By contrast, the coefficient of $z_L1_Targets$ is statistically insignificant. The coefficient of $z_L1_HardCID$ remains positive and significant and is significantly larger than that of $z_L1_SoftCore$ ($F = 4.13$, $p = 0.0421$). These findings indicate that the stronger association of hard disclosure is not attributable solely to the inclusion of carbon-target items in the original soft-disclosure category.

Appendix A Table A3 provides supplementary evidence concerning the composition of carbon disclosure. After controlling for year effects, state-owned enterprises and firms in pollution-intensive industries exhibit significantly higher hard-disclosure shares. Broad regional differences are not statistically significant, although disclosure composition varies across individual provinces. These patterns provide additional evidence that the hard–soft distinction captures systematic differences in reporting practices rather than merely reflecting an arbitrary partition of the aggregate index.

Several control-variable estimates also warrant cautious interpretation. Firm size is positively associated with green invention patenting, while leverage and firm growth are negatively associated with the outcome. The negative leverage coefficient is consistent with the possibility that highly leveraged firms face greater debt-overhang pressure and adopt more conservative investment policies, thereby limiting their willingness or ability to undertake long-horizon and uncertain green R&D projects. The negative growth coefficient may indicate that rapidly expanding firms allocate more short-term resources to capacity expansion, market development, and working-capital requirements, leaving fewer resources available for invention-oriented environmental projects. CEO duality is positively associated with green invention patenting, although this coefficient is not central to the hypotheses examined in this study.

The coefficients of $CashFlow$ and $Big4$ are negative but statistically insignificant. These estimates should therefore not be interpreted as evidence that operating cash flow or $Big4$ audit affiliation reduces green invention patenting. Rather, after controlling for firm and year fixed effects and the other firm characteristics, the analysis does not identify a stable within-firm association between these variables and green invention patenting. Because

the control variables are included primarily to reduce potential confounding rather than to test separate theoretical predictions, their coefficients are interpreted cautiously.

Overall, the results support H2. Both soft and hard carbon disclosure are positively associated with subsequent green invention patenting, but the association is significantly stronger for hard disclosure. Governance-, risk-, and strategy-oriented soft disclosure remains informative, whereas carbon-target disclosure alone is not statistically significant. The estimated magnitudes further indicate that a one-standard-deviation increase in hard disclosure is associated with a substantially larger change in green invention patenting than an equivalent standardized increase in soft disclosure.

4.4. Financing Constraints as a Potential Channel

Green invention patenting typically requires sustained investment, involves uncertain technological outcomes, and generates returns only after relatively long development periods. Firms facing tighter financing constraints may therefore have fewer resources available to support invention-oriented green projects. Carbon disclosure may reduce information asymmetry by providing external stakeholders with more transparent information about firms' environmental strategies, transition risks, and low-carbon activities, thereby potentially improving financing conditions. Given the observational research design and the indirect nature of the financing-constraint measures, the following analyses are interpreted as exploratory evidence consistent with a potential explanatory channel rather than as tests of causal mediation.

Panel A of Table 5 reports the main regression results. Column (1) reproduces the baseline finding that lagged carbon disclosure is positively associated with subsequent green invention patenting. In Column (2), the coefficient of L1_CID is -0.0018 and is statistically significant at the 1% level, indicating that greater carbon disclosure is conditionally associated with lower SA-based financing constraints. Column (3) includes both L1_CID and SA_abs in the green invention patenting equation. The coefficient of SA_abs is -1.8808 and is statistically significant at the 1% level, indicating that stronger SA-based financing constraints are associated with lower green invention patenting. Meanwhile, the coefficient of L1_CID decreases from 0.0103 to 0.0070 but remains positive and statistically significant. This attenuation is consistent with SA-based financing constraints accounting for part of the documented association, although it does not establish causal mediation.

Panel B reports firm-level cluster bootstrap estimates based on 5000 replications. The estimated product of the Path A and Path B coefficients is 0.0033 , with a bootstrap standard error of 0.0004 and a 95% confidence interval of $[0.0026, 0.0040]$. The confidence interval excludes zero, indicating that the product of the two conditional coefficients is statistically different from zero. The conditional coefficient of L1_CID remains positive at 0.0070 , while the corresponding baseline coefficient is 0.0103 . These results are consistent with the proposed financing-constraint channel. However, because the two equations are estimated using observational data and the SA index is an indirect proxy for financing conditions, the statistically significant product term should not be interpreted as identifying a causal indirect effect.

The positive unconditional correlation between L1_CID and SA_abs reported in Table 3 differs from the negative coefficient obtained in the fixed-effects analysis. As shown in Appendix A Table A4, Panel A, the coefficient becomes negative after year fixed effects are introduced and remains negative after firm-level controls and firm fixed effects are included. The sign reversal is therefore consistent with common time patterns and cross-sectional differences affecting the unconditional correlation, whereas the fixed-effects estimate reflects conditional within-firm variation.

Table 5. Exploratory Evidence on the Financing-Constraint Channel.

Panel (A). Main Regression Results						
Variables	(1) GreenInv	(2) SA_abs			(3) GreenInv	
L1_CID	0.0103 *** (0.0009)	−0.0018 *** (0.0001)			0.0070 *** (0.0008)	
SA_abs					−1.8808 *** (0.1439)	
Controls	Yes	Yes			Yes	
Firm FE	Yes	Yes			Yes	
Year FE	Yes	Yes			Yes	
Observations	44,327	44,327			44,327	
Number of firms	4973	4973			4973	
Adjusted R-squared	0.7021	0.9591			0.7116	
Within R-squared	0.0576	0.0481			0.0877	
Panel (B). Firm-Level Cluster Bootstrap Results for the Product Term						
Association Component	Coefficient	Bootstrap SE	z	p-Value	95% CI	
Product term: Path A × Path B	0.0033	0.0004	9.25	<0.001	[0.0026, 0.0040]	
Conditional L1_CID coefficient	0.0070	0.0008	8.36	<0.001	[0.0054, 0.0087]	
Baseline L1_CID coefficient	0.0103	0.0009	11.78	<0.001	[0.0086, 0.0121]	
Path A: L1_CID → SA_abs	−0.0018	0.0001	−15.92	<0.001	[−0.0020, −0.0015]	
Path B: SA_abs → GreenInv	−1.8808	0.1444	−13.02	<0.001	[−2.1639, −1.5977]	
Panel (C). Sensitivity and Temporal-Ordering Tests						
Variables	(1) SA_abs	(2) z_SA_abs		(3) F1_GreenInv		
L1_CID	−0.0018 *** (0.0001)	−0.0064 *** (0.0004)		0.0066 *** (0.0010)		
SA_abs				−1.8418 *** (0.1491)		
Controls	Yes	Yes		Yes		
Size and FirmAge controls	No	Yes		Yes		
Firm FE	Yes	Yes		Yes		
Year FE	Yes	Yes		Yes		
Common financing-index sample	No	Yes		No		
Future innovation outcome	No	No		Yes		
Observations	44,327	38,657		38,481		
Number of firms	4973	4780		4534		
Adjusted R-squared	0.9588	0.9585		0.7223		
Within R-squared	0.0403	0.0522		0.0750		

Note: Panel A reports the main firm fixed-effects regressions. The dependent variable in Columns (1) and (3) is GreenInv, measured as the natural logarithm of one plus the number of green invention patent applications. The dependent variable in Column (2) is SA_abs, with a higher value indicating stronger financing constraints. Panel B reports firm-level cluster bootstrap estimates based on 5000 replications. The product term is calculated as the product of the estimated Path A and Path B coefficients. Because the analysis is based on observational data and SA_abs is an indirect financing-constraint proxy, the product term is interpreted as evidence consistent with a potential explanatory channel rather than as a causally identified indirect effect. Panel C presents additional sensitivity and temporal-ordering tests. Column (1) excludes Size and FirmAge from the financing-constraint equation. Column (2) restricts the analysis to the common sample for which the SA, WW, FC, and KZ indices are available and uses the standardized value of SA_abs. Column (3) uses next-year green invention patenting, F1_GreenInv, as the dependent variable. All models include firm and year fixed effects. Except where otherwise indicated, the same control variables as in the baseline model are included but not reported for brevity. Robust standard errors clustered at the firm level are reported in parentheses. *** indicates statistical significance at the 1% levels, respectively.

Panel C presents additional sensitivity and temporal-ordering tests. Column (1) excludes Size and FirmAge from the financing-constraint equation because these variables are used in constructing the SA index. The coefficient of L1_CID remains virtually unchanged, reducing concern that the result is driven mechanically by overlapping variable construction. Column (2) restricts the analysis to the common sample for which the SA, WW, FC, and KZ indices are available and uses the standardized SA_abs measure. The negative association between carbon disclosure and SA-based financing constraints remains statistically

significant. Column (3) uses next-year green invention patenting as the dependent variable. SA_abs remains negatively associated with future green invention patenting, while L1_CID continues to exhibit a positive and statistically significant coefficient.

Taken together, the SA-based results are consistent with a financing-constraint interpretation of the relationship between carbon disclosure and subsequent green invention patenting. Nevertheless, the evidence should be interpreted cautiously. The analysis does not directly measure borrowing costs, credit availability, external financing volume, or bond spreads, and the alternative financing-constraint indices do not provide fully uniform results. Accordingly, the findings support financing constraints as a potential explanatory channel but do not establish that financing constraints causally transmit the association between carbon disclosure and green invention patenting.

4.5. Additional Heterogeneity Analysis: State Ownership

State-owned enterprises and non-state-owned enterprises differ in their exposure to environmental policy objectives, government supervision, resource access, and social responsibility expectations. SOEs may face stronger administrative guidance and greater pressure to align corporate environmental practices with national low-carbon development priorities. The association between carbon disclosure and subsequent green invention patenting may therefore differ across ownership types.

Table 6 reports the interaction results. Column (1) uses the full baseline sample. Because non-SOEs constitute the reference group, the coefficient of L1_CID represents the conditional association for non-SOEs. The coefficient is 0.0046 and statistically significant at the 1% level. The coefficient of L1_CID $\times$ SOE is 0.0127 and also significant at the 1% level, indicating that the positive association is significantly stronger among SOEs.

Table 6. State Ownership Heterogeneity: Interaction Models and Marginal Effects.

Panel (A). Interaction Models		
Variables	(1) Full Sample	(2) Stable Ownership Sample
L1_CID	0.0046 *** (0.0011)	0.0040 *** (0.0011)
SOE	−0.1188 *** (0.0386)	Omitted
L1_CID $\times$ SOE	0.0127 *** (0.0016)	0.0141 *** (0.0018)
Controls	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes
Observations	44,327	39,293
Number of firms	4973	4539
Adjusted R-squared	0.7039	0.7058
Within R-squared	0.0632	0.0637
Panel (B). Marginal Effects of L1_CID		
Ownership Group	(1) Full Sample	(2) Stable Ownership Sample
Non-SOEs	0.0046 *** (0.0011)	0.0040 *** (0.0011)
SOEs	0.0173 *** (0.0013)	0.0181 *** (0.0015)
Difference: SOEs—Non-SOEs	0.0127 *** (0.0016)	0.0141 *** (0.0018)
F-test of difference	60.07	62.46
p-value	<0.001	<0.001

Note: Panel A reports interaction regressions between lagged carbon disclosure and state ownership. In Column (1), the coefficient of L1_CID represents the conditional association for non-SOEs. The corresponding association for SOEs is calculated as the sum of the coefficients of L1_CID and L1_CID $\times$ SOE. Column (2) excludes firms that change ownership status during the sample period. The main effect of SOE is omitted in Column (2) because ownership status is time invariant in the stable ownership sample and is absorbed by firm fixed effects. Panel B reports the ownership-specific marginal associations and their differences. All models include the baseline controls, firm fixed effects, and year fixed effects. Robust standard errors clustered at the firm level are reported in parentheses. *** indicates statistical significance at the 1% levels, respectively.

Panel B reports the corresponding ownership-specific marginal associations. In the full sample, the estimated association of L1_CID is 0.0046 for non-SOEs and 0.0173 for SOEs, and both estimates are statistically significant at the 1% level. The difference between the two groups is 0.0127, with an F-statistic of 60.07 and a p -value below 0.001.

Column (2) excludes firms that change ownership status during the sample period. In this stable ownership sample, the coefficient of L1_CID is 0.0040, while the interaction coefficient is 0.0141; both are statistically significant at the 1% level. The corresponding marginal association is 0.0040 for non-SOEs and 0.0181 for SOEs. The difference remains statistically significant ($F = 62.46$, $p < 0.001$). The stronger association among SOEs is therefore not attributable to firms switching between state and non-state ownership during the sample period.

The main effect of SOE is omitted in the stable ownership model because ownership status is time invariant for the retained firms and is absorbed by firm fixed effects. This does not affect the estimation of the disclosure coefficient, the interaction term, or the ownership-specific marginal associations.

Overall, carbon disclosure is positively associated with subsequent green invention patenting among both SOEs and non-SOEs, but the association is significantly stronger among SOEs. One possible explanation is that stronger policy alignment, administrative supervision, and environmental responsibility expectations increase the extent to which carbon transparency is accompanied by invention-oriented green activity. This interpretation remains conditional and should not be treated as evidence of a causal ownership mechanism.

4.6. Supplementary Sensitivity Analyses

Although the baseline specifications include firm and year fixed effects and a comprehensive set of firm-level controls, the estimated association may still reflect unobserved time-varying characteristics, persistence in green patenting, or observable differences between firms with different levels of carbon disclosure. This section therefore examines whether the baseline result remains stable under three supplementary specifications: a two-year lagged disclosure measure, a model controlling for prior green invention patenting, and propensity-score matching. These analyses are interpreted as sensitivity tests rather than definitive solutions to endogeneity.

4.6.1. Two-Year Lagged Disclosure

Column (1) of Table 7 replaces L1_CID with L2_CID, a strict two-year lagged disclosure measure. The coefficient of L2_CID is 0.0101 and statistically significant at the 1% level. Carbon disclosure from two years earlier is therefore positively associated with current green invention patenting.

The persistence of the association under a longer temporal separation reduces concern that the baseline result is driven entirely by contemporaneous or short-term timing patterns. Nevertheless, the two-year lag does not eliminate the possibility that persistent environmental strategies or other time-varying firm characteristics influence both disclosure and patenting.

4.6.2. Controlling for Prior Green Invention Patenting

Green invention patenting may be persistent because firms with accumulated technological capabilities and prior patenting experience are more likely to continue invention-oriented green activities. Column (2) therefore includes L1_GreenInv, the strict one-year lag of the dependent variable.

The coefficient of L1_GreenInv is 0.4140 and statistically significant at the 1% level, indicating substantial persistence in green invention patenting. After prior patenting is

controlled for, the coefficient of L1_CID remains positive and significant at 0.0054. The baseline association is therefore not explained solely by firms' previous green invention activity. However, including a lagged dependent variable does not remove all potential omitted-variable concerns.

Table 7. Additional Sensitivity Analyses.

Variables	(1) Two-Year Lag	(2) Lagged DV	(3) PSM Sample
L2_CID	0.0101 *** (0.0010)		
L1_CID		0.0054 *** (0.0006)	0.0092 *** (0.0011)
L1_GreenInv		0.4140 *** (0.0107)	
Controls	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Matching weights	No	No	Yes
Observations	38,417	44,327	40,938
Number of firms	4536	4973	4864
Adjusted R-squared	0.7161	0.7521	0.7151
Within R-squared	0.0541	0.2159	0.0458

Note: This table reports supplementary sensitivity analyses. Column (1) replaces the one-year lagged disclosure measure with L2_CID, a strict two-year lag of aggregate carbon disclosure. Column (2) additionally controls for L1_GreenInv, the strict one-year lag of green invention patenting. Column (3) reports a matching-weighted firm fixed-effects regression using the propensity-score-matched sample. Firms whose lagged carbon disclosure exceeds the annual median are classified as treated. Propensity scores are estimated using the baseline firm characteristics and year indicators. A 1:4 nearest-neighbor matching procedure with replacement, a caliper of 0.05, and a common-support restriction is applied. Each treated observation receives a weight of one, while each matched-control assignment contributes a weight of one-fourth. When a control observation is selected for multiple treated observations, its matching weights are accumulated. Thus, the reported number of control observations refers to unique firm-year observations with positive matching weights rather than the total number of control-match assignments. The control weights sum to the total treated weight, and no additional normalization or rescaling is applied before estimation. The generated matching weights are used directly in Column (3). The fixed-effects estimator removes 91 singleton observations, producing a final estimation sample of 40,938 observations from 4864 firms. All models include the baseline controls, firm fixed effects, and year fixed effects. Firm-clustered robust standard errors are reported in parentheses. These analyses assess the stability of the baseline association and should not be interpreted as establishing causal effects. *** indicates significance at the 1% levels, respectively.

4.6.3. Propensity-Score-Matched Sample

The third sensitivity analysis applies propensity-score matching to reduce observable differences between firms with relatively high and low carbon disclosure. Firms whose L1_CID exceeds the annual median are assigned to the treatment group, while the remaining firms constitute the control group. Propensity scores are estimated using firm size, leverage, profitability, growth, cash flow, board size, board independence, CEO duality, firm age, Big4 audit affiliation, state ownership, and year indicators. A 1:4 nearest-neighbor matching procedure with replacement, a caliper of 0.05, and a common-support restriction is applied.

The original baseline sample contains 20,603 treated observations and 23,724 control observations. After imposing the common-support restriction and retaining observations with positive matching weights, the matched sample contains 41,029 unique firm-year observations from 4955 firms. These observations comprise 20,493 treated firm-year observations and 20,536 unique control firm-year observations.

The number of unique control observations should not be interpreted as the number of individual matching assignments. Under matching with replacement, the same control observation may be selected as a match for multiple treated observations. Each treated observation receives a matching weight of one, while each of its four matched-control assignments contributes a weight of one-fourth. When a control observation is selected more than once, these one-fourth contributions are accumulated in a single observation-level weight. Consequently, a reused control observation appears only once in the matched

dataset but may receive a weight greater than one. The resulting control weights range from 0.25 to 21.5. By construction, the matching weights assigned to the control group sum to 20,493, which equals the total weight of the treated group. No additional normalization or rescaling of the matching weights is performed before the regression analysis.

The generated matching weights are used directly in the subsequent firm fixed-effects regression. During estimation, 91 singleton observations are removed because their firms are represented by only one usable observation in the matched estimation sample. The final weighted regression therefore contains 40,938 firm-year observations from 4864 firms. This reduction results from the requirements of the fixed-effects estimator rather than from an additional matching restriction.

Figure 2 presents the propensity-score distributions of the treated and control groups. The two distributions overlap substantially across most of the propensity-score range, while only a small number of treated observations fall outside the common-support region. This pattern indicates that most treated observations have comparable control observations within the specified caliper.

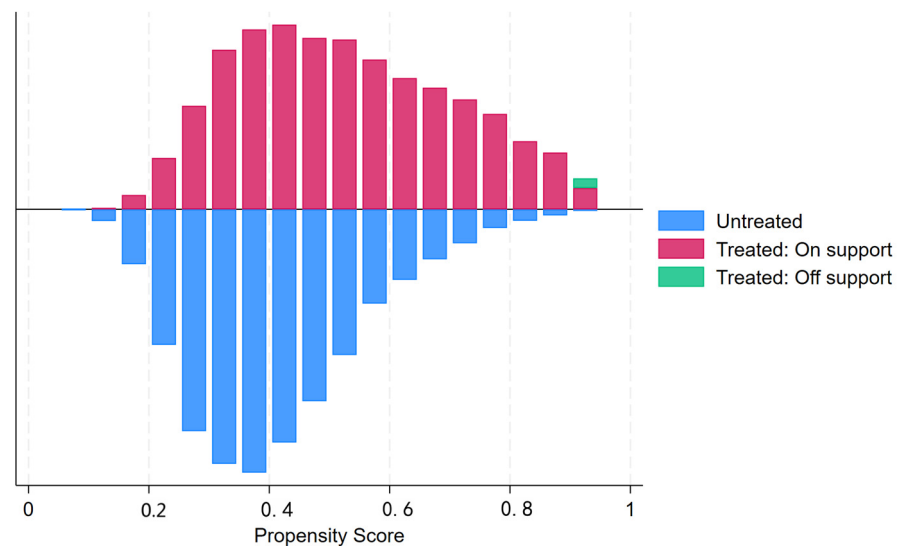


Figure 2. Propensity-Score Distribution and Common Support. Note: This figure presents the propensity-score distributions of treated and control observations. Firms are classified as treated when their lagged carbon disclosure score exceeds the annual median. Treated observations within the common-support region are distinguished from those outside the support. The visual overlap between the treated and control distributions indicates that the common-support condition is satisfied for most treated observations.

Figure 3 reports the standardized percentage bias of the main firm-level covariates before and after matching. Before matching, substantial imbalance is evident for several characteristics, particularly firm size, state ownership, leverage, board size, and Big4 audit affiliation. After matching, using the generated matching weights, the standardized biases of all reported covariates move close to zero. The mean standardized bias decreases from 21.4% to 1.2%, while the median bias declines from 16.8% to 1.2%. Rubin's B decreases from 71.1 to 4.7, and Rubin's R equals 0.83 after matching. These diagnostics indicate a substantial improvement in covariate balance.

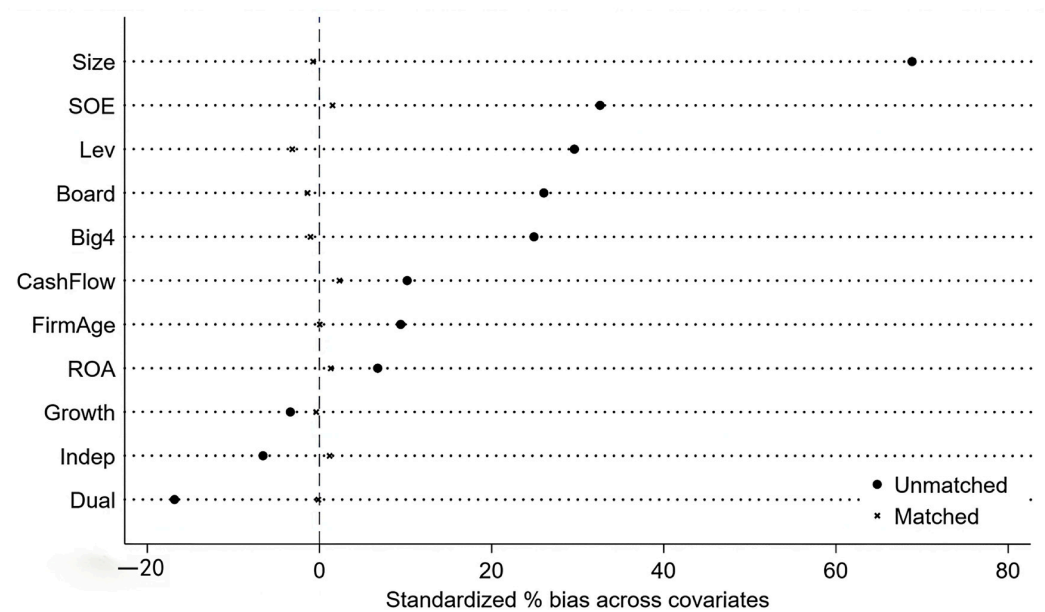


Figure 3. Covariate Balance Before and After Matching. Note: This figure reports the standardized percentage bias of the main firm-level covariates before and after propensity-score matching. Circles represent the unmatched sample, while crosses represent the matched sample calculated using the generated matching weights. After matching, the standardized biases of the reported covariates move substantially closer to zero, indicating improved comparability between the treated and control groups in terms of the observed matching covariates.

Although the post-matching mean differences for leverage and cash flow remain statistically significant, their standardized biases are only -3.2% and 2.3% , respectively. With a large sample, conventional mean-difference tests may remain statistically significant even when the magnitude of the remaining imbalance is small. The standardized-bias and Rubin diagnostics therefore indicate satisfactory overall balance.

Column (3) of Table 7 reports the matching-weighted firm fixed-effects estimate. The coefficient of L1_CID is 0.0092 and is statistically significant at the 1% level. Thus, the positive association between carbon disclosure and subsequent green invention patenting remains present after restricting the analysis to observations with common support and accounting for the frequency with which control observations are used in the matching procedure.

Overall, the supplementary analyses produce results consistent with the baseline findings. The estimated association remains positive when disclosure is lagged by two years, prior green invention patenting is controlled for, and the analysis is conducted using a propensity-score-matched sample. These tests strengthen the robustness of the documented association but do not eliminate unobserved time-varying factors or establish causal identification.

4.7. Robustness Tests

4.7.1. Alternative Outcome and Disclosure Measures

Table 8 examines whether the baseline association is sensitive to alternative measures of green patenting and carbon disclosure. All specifications include the baseline controls, firm fixed effects, year fixed effects, and firm-clustered standard errors.

Table 8. Alternative Outcome and Disclosure Measures.

Variables	(1) GreenApp	(2) GreenInvGrant	(3) GreenInvGrant	(4) GreenInv	(5) GreenInv
L1_CID	0.0110 *** (0.0009)	0.0100 *** (0.0007)	0.0092 *** (0.0009)		
L1_ln_CID				0.0198 *** (0.0065)	
HighCID					0.0377 *** (0.0092)
Controls	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Excluding 2023–2024	No	No	Yes	No	No
Observations	44,327	44,327	34,874	44,327	44,327
Number of firms	4973	4973	4079	4973	4973
Adjusted R-squared	0.7277	0.6316	0.6283	0.6997	0.6998
Within R-squared	0.0655	0.0394	0.0270	0.0500	0.0502

Note: Column (1) uses GreenApp, measured as the natural logarithm of one plus total green patent applications. Columns (2) and (3) use GreenInvGrant, measured as the natural logarithm of one plus granted green invention patents. Column (3) excludes observations from 2023 and 2024 to reduce concerns about the shorter patent-examination window near the end of the sample period. Column (4) uses L1_ln_CID, defined as the natural logarithm of one plus lagged carbon disclosure. Column (5) uses HighCID, which equals one when lagged carbon disclosure exceeds the annual median in the final baseline sample and zero otherwise. All specifications include the baseline controls, firm fixed effects, and year fixed effects. Firm-clustered robust standard errors are reported in parentheses. *** indicates statistical significance at the 1% levels, respectively.

Column (1) replaces GreenInv with GreenApp, measured as the natural logarithm of one plus total green patent applications. The coefficient of L1_CID is 0.0110 and statistically significant at the 1% level, indicating that the positive association also applies to firms' broader green patenting activity.

Columns (2) and (3) use GreenInvGrant, measured as the natural logarithm of one plus granted green invention patents. The coefficient of L1_CID is 0.0100 in the full sample and remains positive and significant at 0.0092 after observations from 2023 and 2024 are excluded. The latter result reduces concern that the grant-based finding is driven by the shorter examination window near the end of the sample. Nevertheless, patent grants do not directly measure technological novelty, commercialization, or environmental effectiveness.

Columns (4) and (5) use alternative disclosure measures. The coefficient of L1_ln_CID is 0.0198 and statistically significant at the 1% level. HighCID, which equals one when lagged disclosure exceeds the annual median, is also positive and significant, with a coefficient of 0.0377.

Overall, the positive association remains stable across total green patent applications, granted green invention patents, a logarithmic disclosure measure, and an above-median disclosure indicator. The result also remains present when recent years are excluded from the grant-based specification.

4.7.2. Sample Timing and Time-Varying Industry and Provincial Shocks

The sample extends through 2024, raising the possibility that recent patent observations are less mature than earlier records. Carbon disclosure and green invention patenting may also respond jointly to time-varying industry transition pressures and province-specific environmental or regulatory conditions. Table 9 therefore examines the sensitivity of the baseline result to recent sample years and higher-dimensional fixed effects.

Columns (1) and (2) exclude 2024 and 2023–2024, respectively. The coefficients of L1_CID are 0.0110 and 0.0109, and both are statistically significant at the 1% level. The positive association is therefore not dependent on observations from the final one or two years of the sample period.

Table 9. Sample-Period and Higher-Dimensional Fixed-Effects Tests.

Variables	(1) Excluding 2024	(2) Excluding 2023–2024	(3) Industry $\times$ Year FE	(4) Province $\times$ Year FE
L1_CID	0.0110 *** (0.0010)	0.0109 *** (0.0012)	0.0082 *** (0.0008)	0.0102 *** (0.0009)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Absorbed	Absorbed
Industry $\times$ Year FE	No	No	Yes	No
Province $\times$ Year FE	No	No	No	Yes
Observations	39,612	34,874	44,264	44,327
Number of firms	4635	4079	4972	4973
Adjusted R-squared	0.6982	0.6974	0.7190	0.7031
Within R-squared	0.0542	0.0501	0.0508	0.0567

Note: Columns (1) and (2) exclude observations from 2024 and from 2023–2024, respectively. Column (3) includes firm fixed effects and industry-by-year fixed effects, while Column (4) includes firm fixed effects and province-by-year fixed effects. The higher-dimensional fixed effects absorb the conventional year fixed effects. All specifications include the baseline control variables. Firm-clustered robust standard errors are reported in parentheses. *** indicates statistical significance at the 1% levels, respectively.

Column (3) replaces conventional year fixed effects with industry-by-year fixed effects, which absorb time-varying regulatory, technological, and transition-related conditions common to firms within the same industry. The coefficient of L1_CID remains positive and significant at 0.0082.

Column (4) includes province-by-year fixed effects to absorb time-varying provincial environmental policies, green finance initiatives, economic conditions, and regulatory intensity. The coefficient of L1_CID remains positive and statistically significant at 0.0102.

Overall, the association between carbon disclosure and subsequent green invention patenting remains stable after recent observations are excluded and after time-varying industry- and province-level conditions are absorbed. These analyses reduce concerns that the baseline findings are driven primarily by late-period patent coverage or common industry and provincial shocks, although they do not eliminate firm-specific time-varying omitted factors.

5. Discussion

The findings show that carbon disclosure is positively associated with subsequent green invention patenting, but the strength of this relationship depends on the informational composition of the disclosure. Hard, metrics- and verification-oriented information exhibits a stronger association than soft disclosure, while financing constraints provide only measure-dependent evidence of a potential explanatory channel. Ownership, pollution exposure, and provincial institutional conditions also shape the relevance of disclosure composition.

5.1. Carbon Disclosure and Green Invention Patenting

The positive association between lagged carbon disclosure and subsequent green invention patenting extends prior research on the economic consequences of environmental reporting. Existing studies link carbon disclosure to information asymmetry, financing costs, emissions behavior, and firm valuation [2–6,10,12]. The present findings suggest that carbon reporting is also related to firms' subsequent involvement in invention-oriented green technological activity.

This relationship may reflect both external and internal information effects. Externally, more extensive disclosure enables investors, creditors, regulators, and other stakeholders to better assess firms' environmental exposure and transition preparedness [2,3]. Carbon reporting may therefore reduce uncertainty surrounding long-term environmental investment and make low-carbon strategies more visible to capital providers.

Internally, collecting emissions information and documenting climate responsibilities may help firms identify operational inefficiencies and technological needs. The reporting process can support coordination, internal monitoring, and resource allocation toward low-carbon projects. This interpretation is consistent with evidence that disclosure regulation and organizational capabilities influence innovation decisions [32–34].

The outcome should nevertheless be interpreted narrowly. Green invention patent applications provide a more focused measure of invention-oriented activity than total green patent counts, but they do not directly capture novelty, citation impact, commercialization, or realized environmental benefits. The findings therefore concern green invention patenting rather than every dimension of innovation quality.

5.2. Disclosure Composition and Verifiability

The decomposition results show that the content of carbon reporting matters beyond its aggregate level. Both soft and hard disclosure are positively associated with subsequent green invention patenting, but the standardized coefficient for hard disclosure is significantly larger. Metrics such as emissions quantities, carbon intensity, emissions decomposition, and verification-related information are generally more comparable and externally assessable than broad commitments or prospective statements [6,31].

Hard disclosure may strengthen accountability because external users can compare reported indicators with subsequent operating outcomes. It may also reflect more developed internal measurement systems, which can help firms identify emissions-intensive processes and evaluate green technology investments [36].

The results do not imply that all soft disclosure is symbolic. After carbon targets are separated from the soft index, governance-, risk-, and strategy-oriented disclosure remains positively associated with green invention patenting. Such information may reflect genuine managerial attention and the integration of climate issues into organizational decision-making.

Carbon-target disclosure alone, however, is not statistically significant. Targets are forward-looking and vary in ambition, scope, timing, and enforceability. Without supporting emissions data, implementation progress, or independent verification, announced targets may impose limited accountability.

These findings refine the greenwashing and selective-disclosure literature [20–22]. Hard disclosure leaves less room for unsupported environmental communication because it is more readily assessed by external stakeholders. At the same time, the significance of the SoftCore component cautions against treating all narrative reporting as greenwashing.

5.3. Ownership and Institutional Conditions

The association between carbon disclosure and green invention patenting is stronger among state-owned enterprises. This pattern is consistent with the closer government supervision, policy obligations, and broader environmental responsibilities faced by Chinese SOEs. Under stronger institutional pressure, carbon reporting may be more closely connected with internal environmental management and technological responses [9,11,19].

The disclosure-composition analysis supports this interpretation. After year effects are controlled for, SOEs and pollution-intensive firms allocate a larger share of their disclosure to hard information. These firms face stronger regulatory scrutiny and greater demand for measurable environmental evidence, which may encourage reporting practices linked to emissions monitoring and operational adjustment.

Broad eastern, central, and western differences are not statistically significant, whereas provincial differences are jointly significant. This suggests that local enforcement, adminis-

trative capacity, policy intensity, and industrial structure may be more relevant than broad regional classifications in shaping carbon-reporting practices.

Overall, the hard–soft distinction appears particularly meaningful where firms face greater environmental exposure, government involvement, and locally specific regulatory pressure.

5.4. *Financing Constraints as a Potential Explanatory Channel*

The SA-index results are consistent with a potential financing-constraint channel. Higher lagged carbon disclosure is associated with lower SA-based financing constraints, while stronger constraints are associated with lower current and future green invention patenting. The bootstrap results further show that the product of the estimated Path A and Path B coefficients is statistically different from zero.

This interpretation is theoretically plausible because green invention projects require sustained expenditure, specialized personnel, and tolerance for uncertain and delayed returns. More informative disclosure may reduce uncertainty concerning firms' environmental strategies and transition exposure, thereby improving the information available to investors and creditors [2,3,10,13–15].

Several tests strengthen the SA-based result. The coefficient remains stable after Size and FirmAge are excluded, persists in the common financing-index sample, and is consistent with a specification linking current constraints to next-year green invention patenting. The positive unconditional correlation between disclosure and SA_abs is also explained by common time patterns, as the sign becomes negative after year effects are introduced.

Nevertheless, the evidence is not consistent across alternative measures. The WW and FC results are statistically insignificant, while the KZ estimate does not align with the SA-based direction. Moreover, the study lacks direct measures of borrowing costs, new credit access, external financing volume, or bond spreads. The financing results should therefore be interpreted as conditional evidence consistent with a possible channel rather than as causal mediation.

A stronger identification strategy based on an exogenous disclosure reform, regulatory discontinuity, or direct financing outcome would be necessary to establish whether financing conditions causally transmit the relationship between carbon disclosure and green invention patenting [39].

6. Conclusions and Implications

6.1. *Conclusions*

This study examines whether the content of corporate carbon reporting, rather than its overall extent alone, is related to invention-oriented green activity among Chinese A-share listed firms during 2009–2024.

The evidence reveals several important patterns. Carbon disclosure in the preceding year is positively associated with subsequent green invention patent applications. This relationship remains stable across alternative timing structures, outcome measures, sample restrictions, matching procedures, and higher-dimensional fixed-effect specifications. Nevertheless, these estimates represent conditional associations and should not be interpreted as establishing that disclosure itself causes firms to innovate.

The composition of disclosure is particularly important. Both soft and hard carbon disclosure are positively related to green invention patenting, but the standardized coefficient for hard disclosure is significantly larger. When carbon targets are separated from the other soft items, information concerning climate governance, risks, opportunities, and strategy remains positively associated with green invention activity, whereas target disclosure alone is not statistically significant. The findings therefore do not imply that narrative disclosure

is inherently symbolic. Rather, they indicate that reporting linked to measurable carbon performance and external assessment carries a stronger association with invention-oriented green activity than stand-alone forward-looking commitments.

The relevance of disclosure composition also differs across institutional settings. State-owned enterprises and pollution-intensive firms devote a larger year-adjusted share of their reporting to hard information, while disclosure composition varies significantly across provinces. The association between aggregate carbon disclosure and green invention patenting is also stronger among state-owned enterprises. These patterns suggest that ownership arrangements, environmental exposure, and local implementation conditions shape how carbon reporting is connected with corporate technological responses.

The financing evidence is more tentative. The SA-based results are consistent with a financing-constraint interpretation, but the WW, FC, and KZ indices do not provide uniform support. The analysis therefore identifies financing constraints only as a possible explanatory channel. It does not establish that financing conditions causally transmit the relationship between carbon reporting and green invention patenting.

Taken together, the findings show that the decision usefulness of carbon reporting depends on what firms disclose and how readily that information can be evaluated. Measurable and externally assessable information appears more closely connected with invention-oriented green activity, while governance and strategy disclosure remains informative when it extends beyond unsupported target announcements.

6.2. Practical Implications

Although the observational research design does not identify the causal effects of changes in reporting requirements or corporate disclosure practices, the documented associations offer several practical implications for regulators, corporate managers, and capital-market participants.

For regulators and standard setters, the findings are consistent with placing greater emphasis on information traceability and comparability rather than disclosure volume alone. Reporting frameworks that encourage the disclosure of emissions quantities, carbon intensity, organizational and value-chain boundaries, calculation methods, emissions decomposition, verification status, and progress against previously announced commitments may provide users with more measurable and externally assessable information. Carbon targets may also be more informative when accompanied by clearly defined baselines, coverage, interim milestones, implementation schedules, and explanations of deviations from planned outcomes. These implications should nevertheless be interpreted as directions suggested by the observed disclosure–innovation associations rather than as evidence of the effects of any specific regulatory intervention.

For corporate managers, the findings suggest that carbon disclosure may be more informative when it is connected with internal measurement and decision systems rather than treated solely as a communication exercise. Producing reliable carbon information generally requires coordination across accounting, operations, procurement, sustainability, risk management, and technology functions. Greater integration among these functions may strengthen emissions monitoring, facilitate the identification of carbon-intensive processes, and provide a more systematic information base for evaluating low-carbon investment and R&D projects. Internal controls and external assurance may further enhance the consistency and credibility of the disclosed information.

For investors and creditors, the results highlight the importance of distinguishing between stated intentions and evidence of implementation. Governance and strategy disclosures may reveal managerial attention to climate-related issues, but targets without supporting performance information should not necessarily be treated as equivalent to

realized environmental progress. Carbon reporting may be more decision-useful when assessed together with firms' technological capabilities, financing conditions, industry exposure, ownership structure, and the regulatory environment in which they operate.

The observed provincial variation further suggests that the implementation of common national reporting principles may need to account for differences in local institutional and technical capacity. Provincial authorities may therefore consider strengthening technical guidance, verification capacity, professional training, and enforcement resources while maintaining common national definitions and measurement principles. However, because the provincial evidence is descriptive, it should not be interpreted as demonstrating that any particular local implementation measure would improve disclosure quality or green innovation outcomes.

6.3. Limitations and Future Research

Several limitations provide directions for further research. First, the empirical design does not isolate exogenous changes in corporate disclosure. Lagged variables, firm fixed effects, matching procedures, and industry-year and province-year specifications reduce some sources of confounding but cannot remove all time-varying omitted factors. Future studies could exploit mandatory reporting reforms, exchange-level rule changes, phased policy implementation, or other institutional discontinuities that provide more credible identifying variation.

Second, green invention applications capture only one dimension of technological activity. They do not directly reveal novelty, citation influence, commercial use, diffusion, or realized environmental benefits. Patent records near the end of the sample may also be less mature, particularly for grants. Future research could combine applications with forward citations, patent claims, originality or generality measures, renewal records, commercialization outcomes, and direct evidence of technological adoption.

Third, the financing analysis relies on indirect firm-level indices. Although the SA-based pattern remains stable in several sensitivity tests, the alternative indices produce mixed results. More direct evidence could be obtained from loan contracts, borrowing rates, credit approvals, external financing volumes, bond spreads, or matched bank–firm relationships.

Fourth, the institutional setting may limit the external validity of the findings. Chinese listed firms operate under distinctive ownership arrangements, policy coordination mechanisms, and provincial enforcement structures. Comparative research could examine whether similar disclosure-composition patterns arise under mandatory climate-reporting systems, more developed assurance markets, or different corporate ownership structures.

Finally, the hard–soft classification captures differences in disclosure content and external assessability, but it does not verify the accuracy of individual statements or identify managerial intent. Quantitative disclosure may also be incomplete or selectively presented. Future studies could combine item-level reporting measures with assurance opinions, restatements, enforcement actions, discrepancies between reported claims and emissions performance, and textual indicators of selective presentation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Form
Big4	Big Four accounting firms
CEO	Chief Executive Officer
CID	Carbon Information Disclosure
CNRDS	Chinese Research Data Services Platform
CSMAR	China Stock Market and Accounting Research Database
CSR	Corporate Social Responsibility
ESG	Environmental, Social, and Governance
FE	Fixed Effects
GHG	Greenhouse Gas
PSM	Propensity Score Matching
R&D	Research and Development
SA	Size-Age Index
SOE	State-Owned Enterprise
ST	Special Treatment
PT	Particular Transfer
VIF	Variance Inflation Factor

Appendix A. Supplementary Measurement and Validation

Table A1. Sample Construction Procedure.

Sample Construction Step	Observations Removed	Observations Remaining
Initial control-variable dataset, 2006–2024	—	59,300
Restrict the source data to 2008–2024	2912	56,388
Exclude financial-sector observations	1275	55,113
Exclude current-year ST, *ST, and PT observations	1980	53,133
Unmatched across the disclosure, patent, and control datasets	1077	52,056
Remove one observation with an invalid governance disclosure score	1	52,055
Exclude 2008 observations retained only for lag construction	1293	50,762
Exclude observations with incomplete baseline variables or without a valid consecutive-year lag	6107	44,655
Singleton observations removed by the fixed-effects estimator	328	44,327
Final baseline estimation sample	—	44,327

Note: Observations from 2008 are retained in the merged dataset only to construct one-year-lagged carbon disclosure variables and do not enter the 2009–2024 baseline regressions. One observation with a governance disclosure score exceeding the documented theoretical maximum is removed before the disclosure indices are reconstructed. All lagged variables are generated using strict consecutive calendar-year observations. Accordingly, observations without data for the immediately preceding calendar year are treated as missing rather than being matched to the previous available firm-year observation. Incomplete observations lack at least one variable required by the baseline specification or a valid consecutive-year lag. The firm fixed-effects estimator removes 328 singleton observations that do not contribute to within-firm identification. The final baseline sample contains 44,327 firm-year observations from 4973 firms. *ST refers to listed companies facing the risk of delisting due to consecutive financial losses.

Table A2. Item-Level Mapping of the Carbon Information Disclosure Index into Soft and Hard Components.

Panel (A). Soft Carbon Disclosure				
Original Dimension	Indicator Symbol	Disclosure Content and Scoring Rule	Maximum Score	Classification in This Study
Governance	gov_boardsupervision	1 if the firm discloses an environmental philosophy or an environmental governance structure; 0 otherwise	1	SoftCore
Governance	gov_managerespon	1 if the firm discloses a management-level body responsible for climate or environmental issues; 0 otherwise	1	SoftCore
Governance	gov_employeeenga	1 point for employee-oriented carbon management mechanisms and 1 point for participation in social green activities	2	SoftCore
Risk and opportunity	risk_managesystem	1 if the firm discloses a climate-related risk management system; 0 otherwise	1	SoftCore
Risk and opportunity	risk_identifiassess	1 if the firm identifies or assesses climate-related financial or business risks; 0 otherwise	1	SoftCore
Risk and opportunity	oppor_identifimanage	1 if the firm identifies or manages climate-related financial or business opportunities; 0 otherwise	1	SoftCore
Strategy	strategy_lctransf	1 if the firm explicitly discloses a low-carbon transition strategy; 0 otherwise	1	SoftCore
Targets and mitigation	targets_carbonreduc	0 for no disclosure, 2 for qualitative carbon-reduction targets, and 4 for quantitative targets	4	Targets
Targets and mitigation	targets_oclimatemanage	2 if the firm discloses other climate-related management objectives; 0 otherwise	2	Targets
Targets and mitigation	targets_ereducmeasures	0 for no disclosure, 2 for qualitative emissions-reduction actions, and 4 for quantitative actions	4	Targets
Targets and mitigation	targets_btprogress	0 for no disclosure, 2 for qualitative disclosure of business-transition progress, and 4 for quantitative disclosure	4	Targets
Subtotal: SoftCore		Governance, risk and opportunity, and strategy items	8	
Subtotal: Targets		Carbon targets, climate objectives, mitigation actions, and transition progress	14	
Total: SoftCID		SoftCore + Targets	22	Soft disclosure

Table A2. Cont.

Panel (B). Hard Carbon Disclosure				
Original Dimension	Indicator Symbol	Disclosure Content And Scoring Rule	Maximum Score	Classification in This Study
Metrics and verification	index_ggescope1	0 for no disclosure, 2 for qualitative Scope 1 emissions disclosure, and 4 for quantitative disclosure	4	Emissions indicators
Metrics and verification	index_ggescope2	0 for no disclosure, 2 for qualitative Scope 2 emissions disclosure, and 4 for quantitative disclosure	4	Emissions indicators
Metrics and verification	index_ggescope3	0 for no disclosure, 2 for qualitative Scope 3 emissions disclosure, and 4 for quantitative disclosure	4	Emissions indicators
Metrics and verification	index_carbonei	0 for no disclosure, 2 for qualitative carbon-intensity disclosure, and 4 for quantitative disclosure	4	Emissions indicators
Metrics and verification	index_echanges	0 for no disclosure, 2 for qualitative disclosure of emissions changes, and 4 for quantitative disclosure	4	Emissions indicators
Metrics and verification	index_edscope1	2 if Scope 1 emissions are decomposed by greenhouse gas, geographic region, or subsidiary; 0 otherwise	2	Emissions decomposition
Metrics and verification	index_edscope2	2 if Scope 2 emissions are decomposed by geographic region or business unit; 0 otherwise	2	Emissions decomposition
Metrics and verification	index_vcinteraction	1 if the firm discloses climate-related interaction or engagement within the value chain; 0 otherwise	1	Value-chain and supply-chain indicators
Metrics and verification	index_updowncm	1 if the firm discloses upstream or downstream supply-chain climate-risk management; 0 otherwise	1	Value-chain and supply-chain indicators
Metrics and verification	index_otherclimateinfo	1 if the firm reports other climate-related indicators; 0 otherwise	1	Other metrics and verification
Metrics and verification	index_verifiability	1 if the disclosed environmental or carbon information is supported by ISO 14001 [40] certification or third-party carbon assurance; 0 otherwise	1	Other metrics and verification
Subtotal: Emissions indicators		Scope 1–3 emissions, carbon intensity, and emissions changes	20	
Subtotal: Emissions decomposition		Decomposition of Scope 1 and Scope 2 emissions	4	
Subtotal: Other metrics and verification		Value-chain, supply-chain, other climate indicators, and external verification	4	
Total: HardCID		Sum of all metrics- and verification-oriented disclosure items	28	Hard disclosure

Table A2. Cont.

Panel (C). Construction of the Disclosure Variables	
Variable	Theoretical Range
Governance	0–4
Risk and opportunity	0–3
Strategy	0–1
SoftCore	0–8
Targets	0–14
SoftCID	0–22
HardCID	0–28
CID	0–50

Note: This table presents the item-level mapping used to decompose the CSMAR Carbon Information Disclosure Index into soft and hard disclosure components. The original index contains 22 indicators with a theoretical maximum score of 50. SoftCID consists of governance, risk and opportunity, low-carbon strategy, and targets and mitigation items. HardCID consists of metrics- and verification-oriented items, including emissions measures, emissions decomposition, value-chain and supply-chain information, other climate indicators, and external verification. Items are classified according to the underlying object of disclosure rather than solely according to the numerical score assigned to a particular observation. Metrics-related items are classified as hard because they concern emissions quantities, intensity, decomposition, or verification, although the original scoring system may award an intermediate score for qualitative disclosure. Target-related items are classified as soft because they primarily represent forward-looking commitments rather than realized emissions outcomes. To address the possibility that some target items contain quantitative information, the additional analysis separately distinguishes SoftCore from Targets. HardShare is calculated only for firm-year observations with positive total carbon disclosure because disclosure composition is undefined when CID = 0. Source: Authors' classification based on the CSMAR Carbon Information Disclosure Index.

Table A3. Validation of Carbon Disclosure Composition Across Institutional and Regional Settings.

Panel (A). State Ownership				
Group	Observations	Unadjusted Mean (%)	Year-Adjusted Mean (%)	
Non-SOEs	26,763	21.9939	21.1494	
SOEs	13,975	21.9679	23.5852	
SOE–Non-SOE difference		−0.0260	2.4358 ***	
Clustered standard error		(0.3243)	(0.3108)	
<i>p</i> -value		0.9360	<0.001	
Panel (B). Pollution-Intensive Industries				
Group	Observations	Unadjusted Mean (%)	Year-Adjusted Mean (%)	
Other industries	31,060	21.5065	21.1808	
Pollution-intensive industries	9678	23.5205	24.5659	
Pollution-intensive–Other difference		2.0140 ***	3.3852 ***	
Clustered standard error		(0.3475)	(0.3326)	
<i>p</i> -value		<0.001	<0.001	
Panel (C). Broad Geographic Regions				
Region	Observations	Unadjusted Mean (%)	Year-Adjusted Mean (%)	
Eastern	28,990	22.3404	22.0354	
Central	6501	20.8674	21.5568	
Western	5247	21.4060	22.2369	
Joint F-statistic		7.2263	0.9437	
Joint <i>p</i> -value		0.0007	0.3893	
Panel (D). Provincial Variation				
Statistic		Unadjusted Results	Year-Adjusted Results	
Number of provinces		31	31	
Minimum provincial mean (%)		16.0365	17.9713	
Province with minimum mean		Hainan	Hainan	
Maximum provincial mean (%)		25.2124	26.4748	
Province with maximum mean		Tibet	Ningxia	
Joint F-statistic			1.9759	
Joint <i>p</i> -value			0.0012	

Note: HardShare is calculated as HardCID/CID for firm-year observations with positive aggregate carbon disclosure. The table is based on 40,738 firm-year observations from 4959 firms in the final baseline sample. Unadjusted means are raw group averages. Year-adjusted means are predictive margins obtained from regressions including year fixed effects. Standard errors for group-difference tests are clustered at the firm level. The regional and provincial *p*-values are based on joint tests of the corresponding indicator variables. All reported means and differences are expressed in percentage points. *** indicates significance at the 1% level.

Table A4. Financing-Constraint Diagnostics and Alternative Measures.

Panel (A). Diagnostic Regressions for the Sign Reversal in the SA-Index Results					
Variables	(1) No Time Controls	(2) Year FE	(3) Size and FirmAge	(4) Full Controls	(5) Firm and Year FE
L1_CID	0.0040 *** (0.0003)	−0.0021 *** (0.0004)	−0.0015 *** (0.0002)	−0.0014 *** (0.0002)	−0.0018 *** (0.0001)
Size and FirmAge	No	No	Yes	Yes	Yes
Other controls	No	No	No	Yes	Yes
Firm FE	No	No	No	No	Yes
Year FE	No	Yes	Yes	Yes	Yes
Observations	44,327	44,327	44,327	44,327	44,327
Number of firms	4973	4973	4973	4973	4973
R-squared	0.0188	0.2000	0.8198	0.8260	0.9637

Table A4. Cont.

Panel (B). Alternative Financing-Constraint Measures in the Common Sample				
Variables	(1) z_SA_abs	(2) z_WW	(3) z_FC	(4) z_KZ
L1_CID	−0.0064 *** (0.0004)	0.0005 (0.0004)	0.0001 (0.0005)	0.0010 * (0.0005)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	38,657	38,657	38,657	38,657
Number of firms	4780	4780	4780	4780
Adjusted R-squared	0.9585	0.8900	0.8769	0.8422
Within R-squared	0.0522	0.6182	0.5070	0.6288

Note: Panel A reports sequential regressions designed to explain the difference between the positive unconditional correlation between L1_CID and SA_abs and the negative coefficient obtained from the firm fixed-effects specification. The dependent variable in all Panel A models is SA_abs. Column (1) includes no time controls. Column (2) introduces year fixed effects. Column (3) additionally controls for firm size and firm age. Column (4) includes the full set of firm-level controls and year fixed effects. Column (5) further introduces firm fixed effects (R-squared reported is the overall R²). Panel B reports common-sample regressions using the standardized SA, WW, FC, and KZ financing-constraint indices as dependent variables. The common sample contains observations for which all four financing-constraint measures and the variables required by the baseline specification are available. All Panel B models include the full set of firm-level controls and firm and year fixed effects. The indices are standardized within the common estimation sample without changing their original directional interpretation. For SA_abs, a higher value indicates stronger financing constraints. The signs of the WW, FC, and KZ estimates are interpreted according to the original construction of the respective indices. Robust standard errors clustered at the firm level are reported in parentheses. * and *** indicate statistical significance at the 10% and 1% levels, respectively.

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