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Research article

Does climate change exposure affect the intensive and extensive margins of corporate R&D investment?

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Abstract: In this paper, I investigate how climate change exposure affects extensive and intensive margins of corporate R&D investment. Using firm-level climate change exposure data, the empirical findings indicated that climate change exposure positively and significantly affects both intensive and extensive margin of corporate R&D investment. I show that carbon intensive firms significantly increase their extensive and intensive margins of corporate R&D in response to an increase in climate changes. Using difference-in-differences (DID) regression analysis, I found that firms in treated States invest significantly more in corporate intensive margins of R&D after the adoption of Renewable Portfolio Standards. The results are robust with other measures of climate change exposure and with the inclusion of industry and macroeconomic factors. Moreover, I found that firms in carbon intensive industries engage more in R&D than firms in green industries.

Keywords: climate change exposure; R&D; extensive margin, intensive margins, capital-intensive industries

JEL Codes: G11, G30, D81, O3, Q54

1. Introduction

Investments in research and development (R&D) by firms play an integral part in determining long-term productivity growth and improving firm value through innovation. Therefore, investing in

R&D increases a firm's productive capacity and income-generating potential (Dynan, 2021). R&D helps firms identify new opportunities, create innovative products and services, and brings these innovations to market through strategic product launches. The allocation of resources to research and development is categorized into two components: the amount dedicated to R&D spending and the decision to engage in R&D. This differentiation corresponds to the firm-level distinction between the extent of investment (intensive margin) and the choice to invest or not (extensive margin) in R&D. Climate change can have a significant influence on firms' activities, increase investment uncertainty, and raise financial risks for innovation and R&D. Climate change risks drive firms to increase their capabilities for R&D, as they adapt to environmental challenges, innovate sustainable solutions, and capitalize on emerging opportunities. Therefore, climate-related risks could also increase firms' capacity to engage in R&D and innovation.

I aim to fill the gap by investigating how climate change exposure impacts R&D margins, specifically how climate-related uncertainties influence organizations' decisions to invest in R&D activities and how much spending is made on R&D investments. Uncertainty related to climate change has been demonstrated to influence research and development (R&D) investment decisions significantly. (Jung & Kwak, 2018; Wang et al., 2014). According to the strategic growth option theory posited by Abel & Blanchard (1986) and Kulatilaka & Perotti (1998), when there is a strong strategic advantage, more uncertainty can lead to more investment in growth options because it is seen as an opportunity. In line with this theory, climate change exposure would have a positive relationship with R&D investment when seen as an opportunity but a negative effect of climate change exposure on R&D when seen as a threat. Firms gain a competitive advantage and improve their future growth when they invest during uncertainty. Investing during periods of high uncertainty could be a valuable opportunity to build trust with stakeholders, sustain a competitive edge, and increase future market value. Studies by Jung & Kwak (2018) and Wang et al. (2014) show that uncertainty has an impact on R&D investment. Real options models (McDonald & Siegel (1986) and Dixit & Pindyck (1994) emphasize that the interaction of capital irreversibility and uncertainty generates option value to delay investment. Because this option's value increases with uncertainty, investment is expected to decrease as uncertainty rises.

To measure climate change exposure, I employ the climate change exposure measure from Saunter et al. (2023). A major challenge for climate change studies is the difficulty in quantifying firm-level climate change exposures[1]. Sautner et al. (2023) created firm-level climate change exposure data using a machine learning method to create firm-level time-varying metrics of climate change exposures. The measure counts the frequency of specific climate change bigrams in the earnings conference call transcripts, then divided by the overall number of bigrams in the transcript.[2] The authors demonstrate that their methods capture firm-level exposures to physical and regulatory shocks caused by climate change. Therefore, firm-level climate change exposure refers to the extent to which a firm or business is vulnerable to the potential risks and opportunities associated with climate change (Cardona et al., 2012). Climate change exposures of firms are affected by many factors, such as climate opportunity (renewable energy, electric vehicles, and sustainable agriculture), physical (sea level rises and natural disasters), and

[1] It is difficult to properly quantify firm-level climate change exposure because climate change's effects on firms are very uncertain varies across firms, and there is no consensus on how to estimate firm-level climate change exposure.

2 The authors modified the climate change exposure data so that the topic measures have zero values when climate change exposure is zero. Out of more than 10,000 firms, only 10% of these firms have zero values.

regulatory shocks (carbon taxes, cap, and trade markets)[3]. The benefit of using climate change exposure by Sautner et al. (2023) is that it may not always translate into environmental, social, and governance (ESG) related activities as other measures (Environmental, Social, and Governance and Corporate Social Responsibility scores). Instead, it can emerge in a variety of outcomes, such as CEO equity incentives (Hossain et al., 2022), corporate social responsibility (Mbanyele & Muchenje, 2022), firm-level total factor productivity (Ren et al., 2022), cash holdings (Heo, 2021) and leverage (Ginglinger & Moreau, 2022), which standard measures may not fully reflect. In this paper, I examine how climate change exposure affects R&D margins at the firm level and find it essential to explain how firm investment decisions respond to climate change exposure. I use the climate change exposure measure identified by Sautner et al. (2020) because the measure exhibits cross-sectional and time-series variations, better captures firm-level variations and is more specific than ratings.

A large volume of empirical studies provides a relationship between firm and market-level characteristics and firm R&D (Bernstein, 2015; Dong & Gou, 2010; Faleye et al., 2014; Lin et al., 2011). However, only a few empirical papers have focused on the impact of climate uncertainty on corporate R&D investment (Li et al., 2022; Hoang, 2022). My study differs from other studies as I focus on US R&D investment using a firm-level measure of climate change exposure. Researchers in this area analyze variations in the aggregate measure of climate risk exposure (Global climate risk index, ESG scores, and vulnerability index). I contribute to the literature using a novel measure of climate change exposure that enables me to explore how the variation in firm-level climate change exposure affects corporate investment-related decisions.

I examine the impact of climate change exposure on corporate R&D investment using data from 2,296 U.S. firms (2002–2022). Baseline results show a positive relationship between climate change exposure and R&D-intensive margins, with a one standard deviation increase in exposure leading to a 3.32%age point rise in R&D intensity. This is a reasonably meaningful impact as the average R&D intensive margin is 5.5%. This relationship holds after controlling firms, industries, states, and macroeconomic factors, suggesting firms invest in R&D to enhance competitiveness and adapt to climate challenges.

Cross-sectional analysis reveals stronger effects for carbon-intensive and manufacturing firms, with one standard deviation increase in climate change exposure raising R&D by 25.6% and 8.3%, respectively. The probability of R&D investment also rises with climate exposure, particularly for carbon-intensive firms (24.23%) compared to green firms (20.16%). Key channels driving R&D include vertical integration, growth opportunities, and investment tax credits, improving supply chain resilience, incentivizing innovation, and reducing R&D costs.

An event study around the Paris Agreement shows that R&D-intensive margins increased when the U.S. joined (2015–2016), declined during withdrawal announcements (2017–2020), and rebounded upon rejoining. A difference-in-differences analysis using the Renewable Portfolio Standard (RPS) as an exogenous shock confirms a causal relationship: firms in RPS-adopting states increased R&D investment post-Paris Agreement, highlighting the role of policy in driving climate-focused innovation.

This paper adds to several lines of research. First, this paper complements the growing studies of how firms respond and adapt to climate change. Other studies show that climate change exposure influences

3 The term "exposure" is characterized by the proportion of the dialogue within a transcript dedicated to pertinent subject matter, specifically focusing on climate change opportunities. Bigrams are combination of two words that ensure the topic is relevant to climate change. Some of the keywords captured are "renewable energy," "electric vehicle," "clean energy," "new energy," and "wind power".

cash-holding decisions (Heo, 2021), corporate social responsibility (Mbanyele & Muchenje, 2022), and corporate tax avoidance, while Ginglinger & Moreau (2022) find a negative relationship between climate change exposure and corporate leverage. I extend the work of Wang et al. (2017), who examined uncertainty at the macro policy level. I use micro-level data and a wider sample of firms to conduct firm-level analysis of climate change impacts. My findings highlight key implications for U.S. corporate management and policymaking. Firms, especially in carbon-intensive sectors, should align R&D strategies with climate risks by investing in green technologies, climate-resilient products, and sustainability practices to adapt to regulatory changes and shifting consumer preferences. Policymakers can promote such investments by strengthening climate regulations, like Renewable Portfolio Standards or carbon pricing, and designing support mechanisms for industries vulnerable to climate risks. These efforts will drive innovation, enhance competitiveness, and foster a sustainable economic transition.

Second, this study adds to the growing body of literature by examining the impacts of climate policies on corporate investment decisions. The evidence from this study provides the mechanism by which climate change exposure can affect firm decisions. Also, firms must implement policies in the context of climate change, which is valuable for making informed decisions regarding environmental sustainability and climate adaptation.

Third, this study contributes to the R&D investment literature. Researchers examine the determinants of firms' R&D, focusing on firm fundamentals (Lee & Hwang, 2003; Lai et al., 2015; Shin & Lee, 2022), but the influence of climate change on R&D investment is under study. Therefore, this study contributes to this literature by introducing climate change-related opportunities as an additional influential factor in the contemporary low-carbon landscape, further establishing the link between climate change and R&D investments.

The remainder of the paper is organized as follows. In the second section, I set out the literature and develop the hypotheses. In the third section, I introduce the empirical method and definition of the variables. In section four, I present the empirical results. In section five, I conclude the study.

2. Literature review and hypothesis development

2.1. Theoretical underpinning

The theoretical mechanisms through which climate change influences R&D investment can be effectively analyzed through the lens of real options theory, as articulated by foundational works such as Myers (1977), McDonald & Siegel (1986), and Dixit and Pindyck (1994). This framework posits that firms facing heightened uncertainty tend to defer or reduce investments due to the increased value of maintaining flexibility and avoiding irreversible commitments. Climate change, as a source of profound environmental, regulatory, and market uncertainty, amplifies this dynamic, leading to a reduction in R&D investment. The inherent unpredictability of climate-related risks, such as regulatory shifts, physical impacts, and transitional challenges, elevates the option value of waiting, thereby discouraging firms from committing to long-term, costly R&D projects.

Empirical evidence robustly supports this theoretical perspective. For instance, Czarnitzki & Toole (2007) demonstrated that rising market uncertainty, akin to the uncertainty induced by climate change, correlates with diminished R&D expenditures. Similarly, Julio and Yook (2012) highlighted that firms reduce investment expenditures by 4.8% on average during periods of heightened uncertainty, such as election years, which parallels the climate-induced policy uncertainty firms face. Further, Wang et al. (2014) and Gulen & Ion (2015), utilizing the Baker et al. (BBD) (2016) policy uncertainty index, established a negative relationship between policy uncertainty and corporate investment, reinforcing the applicability of real options theory to climate-related uncertainty. Chen et al. (2016) further corroborated this view, showing that political uncertainty, including changes in leadership, significantly curtails corporate investments. Collectively, these findings underscore the theoretical proposition that climate change, by exacerbating uncertainty, incentivizes firms to delay or reduce R&D investments, aligning with the predictions of real options theory. This body of literature thus provides a compelling framework for understanding the mechanisms through which climate change influences corporate innovation strategies. Therefore, I hypothesize that:

Hypothesis 1a: Climate change exposure significantly reduces the intensive and extensive margin of R&D investment, aligning with the real options theory.

Conversely, the theory of strategic growth options, introduced by Kulatilaka and Perotti (1998), offers a countervailing perspective to real options theory, positing that uncertainty can serve as a catalyst for investment in growth opportunities, particularly in competitive environments. This framework suggests that firms may perceive uncertainty not solely as a deterrent but also as a strategic opportunity to invest in projects with the potential for high returns. Under this paradigm, uncertainty creates valuable growth options and delaying investments risks allowing competitors to seize emerging opportunities. This theoretical lens is particularly relevant for understanding how firms navigate climate-induced uncertainty in their R&D decisions, as it highlights the potential for proactive investment in innovation to secure competitive advantages in the face of environmental and regulatory shifts.

Empirical studies provide robust support for this perspective. Vo & Le (2017) demonstrated that uncertainty, measured through idiosyncratic stock return volatility, is positively associated with increased R&D spending, suggesting that firms may interpret uncertainty as a signal to invest in innovation to capture future growth opportunities. Similarly, Ross et al. (2018) found that uncertainty stimulates R&D investment, particularly among firms with strong human capital, diversified innovation portfolios, and those operating in mature industries. These findings underscore the importance of firm-specific capabilities and competitive dynamics in shaping the relationship between uncertainty and R&D investment. This body of evidence highlights the dual nature of uncertainty in influencing corporate innovation strategies, with climate change serving as both a source of risk and a potential driver of strategic growth-oriented R&D investments. Based on the growth options theory, I expect climate change exposure will improve the intensive and extensive margins of R&D. I hypothesize that:

Hypothesis 1b: Climate change exposure increases the extensive and intensive margin of R&D investment based on the strategic growth options theory.

The empirical papers on the relationship between uncertainty and R&D investment are mainly based on uncertainty at the macro level. However, this study uses micro-level uncertainty that helps to understand better why and how firms respond to climate change exposures. In cases where there is climate change exposure and discretion regarding investment, the investment opportunity encompasses two choices: A real option and a growth option. These two options share a common feature akin to options in that their value increases as climate change exposure rises.

The moderating influence of firm characteristics: Vertical integration and growth opportunities

Vertical integration measures the number of operations carried out within the confines of a firm. Vertical integration also refers to the ownership of various production and operation links in the supply chain, so interactions between firms are changed to be within the same firm, and resource allocation is controlled by the authority within the organization.

Yuan et al. (2022) analyze the impact of vertical integration on corporate value under uncertainty shock using cross-sectional data during the COVID-19 pandemic outbreak. They observe a significant and positive relationship between vertical integration and the cumulative abnormal return of individual stock during the pandemic outbreak.

Vertical integration is a moderating factor in the relationship between climate change and R&D. It provides greater control over supply chains, enhancing adaptability and resilience and improving coordination throughout production. Vertical integration enables firms to make environmentally conscious decisions and effectively develop innovative solutions to address climate change-related challenges. Under the shock of uncertainty caused by the COVID-19 pandemic, firms with high vertical integration are less affected by the increased external transaction costs so that vertical integration could enhance corporate value. Therefore, climate firms with vertical integration are less affected by the increased external transaction costs when exposed to climate-related policy, so vertical integration could enhance R&D. The hypothesis is that:

Hypothesis 2: Vertical integration increases the positive and intensifies the relationship between firm-level climate change exposure and intensive margins of R&D investment.

The moderating influence of firm characteristics: Growth opportunities

A growing firm might invest more in R&D to sustain and continue its growth. In a period of uncertainty, firms with high growth opportunities invest more in R&D (Li et al., 2022; Atanassov et al., 2017; Van Vo & Le, 2017). Firms with great capacity for growth that face climate change-related concerns may expand R&D to innovate and exploit eco-friendly market demand or cut R&D due to resource allocation and regulatory uncertainties. The decision is influenced by risk tolerance, financial capability, and perceived trade-offs between short-term and long-term growth objectives in the context of climate change challenges.

Therefore, I propose a hypothesis that:

Hypothesis 3 Firm-level climate change exposure and growth opportunities positively affect intensive margins of corporate R&D investment.

The moderating role of industry characteristics: Heavy emitter industries

According to Ma et al. (2023), firms exposed to climate change opportunities are greatly motivated to expand investment. However, the effect varies significantly between industries. Carbon-intensive industries increase their R&D efforts in response to climate change due to regulatory compliance, reputation management, risk mitigation, cost reduction, access to new markets, competitive advantage, and long-term viability considerations. However, firms tend to reduce investment or divest when faced with uncertainty until they have acquired more information to enable better-informed decision-making (Hoang, 2022; Tran et al., 2021, Kim & Kung, 2017;). Based on this understanding, I hypothesize that:

Hypothesis 4: Intensive and extensive margins of R&D investment increase for carbon-intensive firms as climate change exposures increase.

The literature on climate risk's impact on corporate activities and innovation reveals a dual narrative, highlighting both challenges and opportunities. On one hand, extreme weather events have been shown to damage fixed assets (Xu & Xu, 2023), disrupt operations and productivity (Pankratz & Schiller, 2023; Lin & Shen, 2023), and weaken firm performance (Huang et al., 2018; Chen et al., 2023)). Additionally, climate risk is linked to higher capital costs (Huynh et al., 2020; Javadi & Masum, 2021), further limiting firms' financial flexibility.

On the other hand, some studies suggest climate risk can create opportunities. For instance, renewable energy firms see improved investment efficiency after extreme weather events (Yu et al., 2022), while other enterprises increase investments to regain market advantages post-disasters (Rao et al., 2022). Climate risks also enhance ESG transparency (Huang et al., 2022) and CSR performance (Ozkan et al., 2023), with firms in renewable energy and related sectors benefiting directly (Sautner et al., 2023). Integrating climate concerns into decision-making can lower capital costs, boost firm value, and reduce portfolio risks (Chava, 2014; Ghoul et al., 2018; Hoepner et al., 2016; Gibson & Krueger, 2018).

Innovation plays a critical role in addressing climate challenges. Studies show that technological advancements improve adaptation in agriculture (Smithers & Blay-Palmer, 2001; Bosello et al., 2009) and mitigate climate-related productivity constraints (Chhetri & Easterling, 2010). Keane & Neal (2018) further highlight innovation as a key adaptation strategy. However, research on climate risk's direct impact on corporate innovation is limited and inconsistent. While some researchers found that natural disasters spur technology patents (Miao & Popp, 2014), others found that air pollution and rising temperatures hinder innovation by exacerbating financial constraints (Tan & Yan, 2021)

In conclusion, while literature underscores the dual nature of climate risk, significant gaps remain in understanding its influence on corporate innovation. I aim to provide new insights into this relationship, offering a clearer perspective on how climate change exposure affects the intensive and extensive margin of R&D investments.

3. Methodology

3.1. Data and samples

I construct the sample by merging firm-level climate change exposure data with firm-level and industry-specific data with a unique identifier (GVKEY), and the new, created data is merged with macroeconomic data. Firm and industry data is obtained from Compustat North America for publicly listed U.S. firms. The firm-level climate change exposure data is obtained from Sautner et al. (2023) and macroeconomic data from Federal Reserve Economic Data (FRED) St. Louis. The sample begins in 2002 since that is when the firm-level climate change exposures data became available. The initial sample contains 30,061 firm-year observations.

I exclude financial firms with Standard Industrial Classification (SIC) codes 6000–6999 and utility firms with SIC codes 49,000–49,999 due to disparities in accounting practices and regulation requirements. Similarly, I also exclude firms having negative total assets and sales. Firm-year observations with missing data were dropped for all control variables used in the major models. The final sample is unbalanced panel data, including 24923 firm-year observations with 2296 firms from 2002–2022. The graph in Figure 1 shows an upward trend in climate change exposure from 2002 to 2022. From 2002–2011, values are stable with minor fluctuations. From 2012–2016, exposure increases, stabilizing around 2014–2016. From 2017–2022, there is a marked rise, reflecting heightened regulatory, stakeholder, and global climate awareness. Also, the graph in Figure 2 shows how intensive margins of

R&D (R&D per sales) change over the years. The graph in Figure 3 looks similar to Figure 2, when R&D is divided by total assets and R&D intensive changes from 2002 to 2022.

Table 1A shows the number of firms that change with years. The year 2019 has the highest number of firms while 2022 is the year with lowest number of firms. Table 1B illustrates varying climate change exposure across industries by 2-digit SIC codes. Manufacturing shows the highest exposure (0.027394), suggesting significant environmental impact. Wholesale has the lowest (0.000193), indicating minimal exposure. Differences across agriculture, metal, construction, retail, and service sectors underscore diverse environmental challenges.

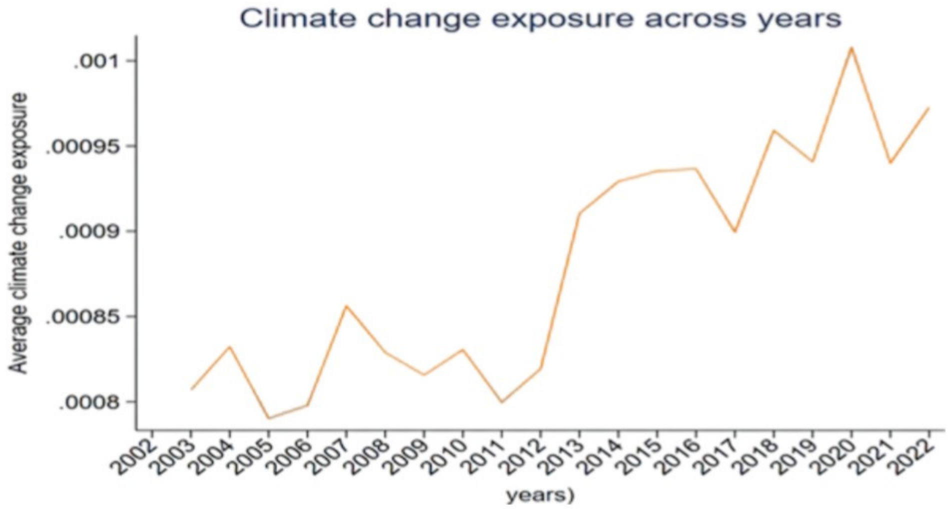

Figure 1. A graph showing average climate change exposure from 2002 to 2022.

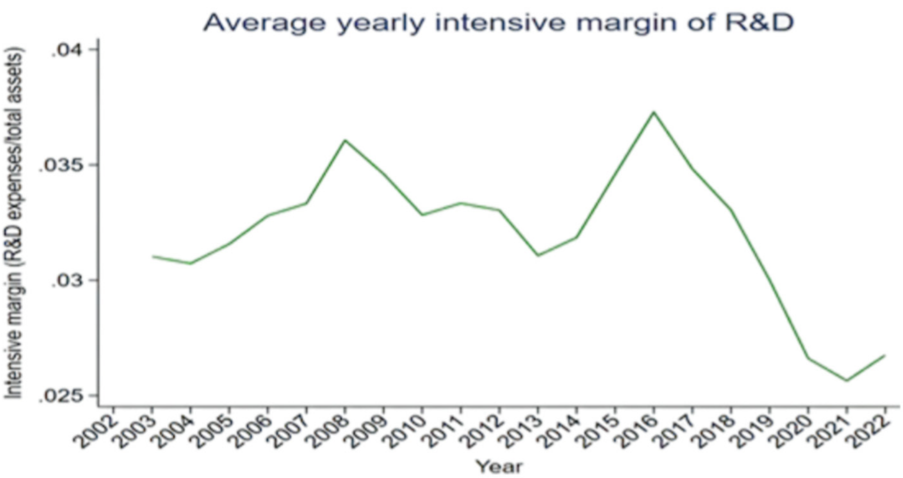

Figure 2. A graph showing average intensive margin of R&D (R&D per total assets) from 2002 to 2022.

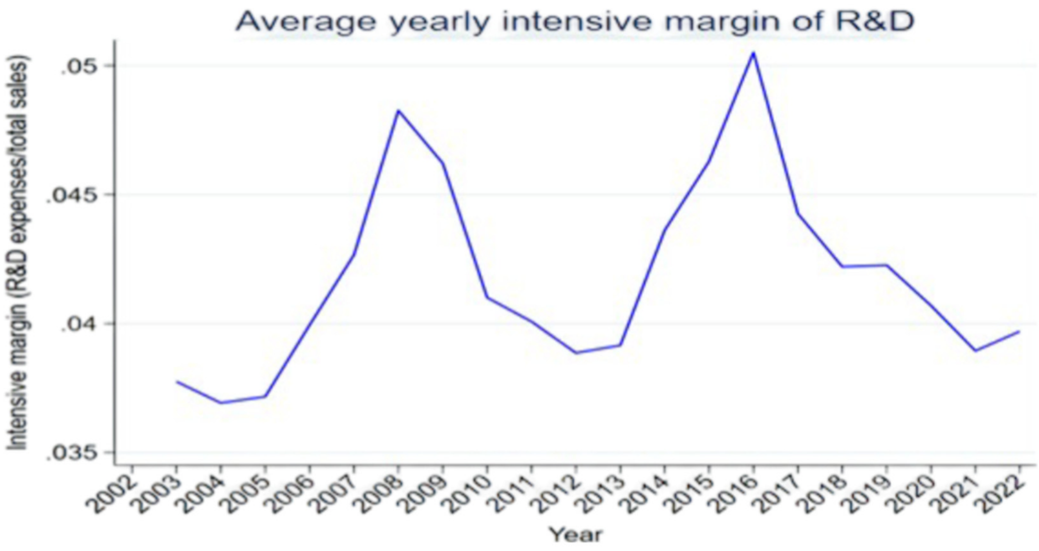

Figure 3. A graph showing average intensive margin of R&D (R&D per total sales) from 2002 to 2022.

Table 1A. Number of firms over years.

Year	Number of firms by year
002	1070
2003	1795
2004	1724
2005	1621
2006	1530
2007	1419
2008	1349
2009	1293
2010	1229
2011	1164
2012	1113
2013	1083
2014	1125
2015	1173
2016	1197
2017	1169
2018	1122
2019	1,953
2020	1063
2021	978
2022	775

Table 1B. Climate change exposure by Industry (2-digit SIC code).

Major industry base on SIC2	Number of firm-year observations	Climate change exposure
Agriculture production	75	0.000806
Metal	1658	0.003887
construction	501	0.002269
manufacturing	15336	0.027394
wholesale	1118	0.000193
Retail	2181	0.003165
service	4054	0.004034

Tables 1C and 1D show the industry breakdown of carbon-intensive and green industries. Carbon-intensive industries are firms with the highest concentration of energy use and carbon emissions, while the green industry is made up of firms that implement environmentally friendly policies and practices. Chemicals and allied products have 210 firms, while the oil and gas industry has 106 firms with metal mining having the least number of firms (9 firms). Industrial machinery and equipment have 642 firms followed by services with 342 firms in the green industry. A total of 380 firms reported missing R&D, while 1916 reported positive R&D. Of 380 firms that reported zero R&D, 336 firms are non-manufacturing firms, and 44 are manufacturing firms. Table 1E shows firms with highest climate change exposure over years with ZIX corporation having the highest value (0.044). All control variables are winsorized at the 1st and 99th percentiles to decrease the impact of outliers and data errors on my analysis.[4]

Table 1C. Number of firms in the carbon intensive industry.

SIC- 2 Digit industry- Carbon intensive industry	**Number of firms**
Metal Mining	10
Oil and gas extraction	106
Food and kindred products	49
Lumber and wood products	22
Paper and allied products	17
Chemicals and allied products	220
Petroleum and coal products	16
Rubber and miscellaneous plastic products	29
Stone, Clay, Glass, and Concrete Products	17
Primary metal	44
Transportation equipment	33
Railroad transportation	11
Trucking and warehousing	19
Water transportation	11
Transportation by air	21
General Merchandize stores	21
Electric, gas and sanitary services	36

Carbon intensive industries are industries that emit high carbon.

[4] Out of the 2296 distinct firms, 682 firms representing about 25% fall into carbon intensive industry while the remaining 1614 unique firms fall into the green industries representing 75%.

Table 1D. Number of firms in the carbon intensive industry.

SIC- 2 Digit industry- green industry	Number of firms
Agriculture production and services	9
Construction	128
Tobacco products	2
Apparel and other textile products	28
Furniture and fixtures	20
Printing and publishing	42
Leather and leather products	10
Industrial machinery and equipment	622
Transportation and communications	78
Wholesale and retail trade	275
Services	285
Health and legal services	115

Green industries are industries that emit low carbon into the atmosphere.

Table 1E. Firms with highest climate change exposure over years.

Year	Firms	climate change exposure
2002	CSX CORP	0.03119
2003	ELXSI CORP	0.03616
2004	ELXSI CORP	0.03063
2005	CSX CORP	0.03064
2006	DAILY JOURNAL CORP	0.03332
2007	DAILY JOURNAL CORP	0.02935
2008	DAILY JOURNAL CORP	0.03140
2009	ELXSI CORP	0.03063
2010	CPAC INC	0.02182
2011	TACTILE SYSTEMS TECHNOLOGY	0.02011
2012	ZIX CORP	0.02933
2013	ZIX CORP	0.03302
2014	CLEARONE INC	0.03966
2015	ZIX CORP	0.04460
2016	LIBERTY EXPEDIA HOLDINGS INC	0.03068
2017	MICRON SOLUTIONS INC	0.03341
2018	LIBERTY EXPEDIA HOLDINGS INC	0.04049
2019	LIBERTY EXPEDIA HOLDINGS INC	0.04333
2020	AMERICAN WOODMARK CORP	0.03420
2021	GOOD TIMES RESTAURANTS INC	0.03268
2022	TACTILE SYSTEMS TECHNOLOGY	0.0159

3.2. Baseline model specification

I follow the estimation techniques of Barnerjee & Gupta (2021) to construct control variables and then merge the sample with firm-level climate change measures. I begin my analysis with a fixed effect model for my baseline regression model to examine how climate change exposures influence intensive margins of R&D. Equation 1 captures how climate change exposures affect intensive margins of R&D after controlling for firm and industry characteristics in equation 1. Furthermore, I lag explanatory variables by one period to prevent problems of simultaneity and reverse causality (Roberts & Whited, 2013; Mairesse & Mohnen, 2010).

$$R\&D\_int_{it} = \alpha + \beta_1 CCExposure_{i,t} + \sum \beta_{k,j} X_{k,j,t-1} + \gamma_t + \varpi_i + \phi_j + \varepsilon_{i,t} + \upsilon_{j,t} \tag{1}$$

where i indicates firms, j represents industry, and t indicates years. The dependent variable is the intensive margins of R&D, measured as the ratio of R&D expenditure to total assets. The main variable of interest, $CCExposure_{i,t}$ is the firm-level climate change exposure constructed by Sautner et al. (2023). $X_{k,j,t-1}$ is a vector of firm and industry specific control variables, such as firm size, firm age, profitability, leverage, capital investments, dividend dummy, cash holdings, book to market ratio, sales growth, market, and the Lerner index. γ_t is the time specific and $\varepsilon_{i,t}$ *and* $\upsilon_{j,t}$ are the error term. I account for firm and industry fixed effects in the regression model. I include firm fixed effects, which are important because they account for time-invariant firm features that may be unobservable. Robust standard errors are clustered at the firm level to address the issue of heteroscedasticity.

The model specification to investigate how climate change exposure affects extensive margins of R&D is expressed in equation 2 using conditional logit regression. Conditional logit regression is preferred over traditional logit when firm fixed effects are included in panel data analysis. It addresses the incidental parameter problem by focusing on within-firm variation, controlling for unobserved, time-invariant firm characteristics, and ensuring consistent estimates. In contrast, traditional logit conflates within- and between-firm effects, leading to potential bias. Conditional logit is most effective when there is sufficient variation in the dependent variable within each firm, making it well-suited for studying firm changes over time. Standard maximum likelihood estimators[5] for binary response panel data models, which use individual heterogeneity as a parameter, are inconsistent when the time dimension (Time) is fixed, and the cross-section size (number) grows. The issue develops as the number of unit-specific unobserved effects accumulates. Chamberlain (1980) suggests that the latent model errors of the conditional logit technique use logistic distribution. One advantage of this strategy is that it does not specify the distribution of the unobserved effect. I consistently estimate the partial effects of continuous factors and their impact on the log-odds ratio. One assumption of using the conditional likelihood function is that it is assumed that the fixed effects and explanatory variables are not correlated with the error term. I use the conditional logit proposed by McFadden because all covariates vary by choice among firms. Then, McFadden proposed the conditional logit model in this form

$$\Pr\ (R\&D\_ext_i = j | X_{i0} \dots X_{ik}) = \frac{\exp(X'_{ij}\mathcal{B})}{\sum_{i=0}^{j} \exp(X'_{ij}\mathcal{B})}, \tag{2}$$

j = 0, ..., j. Parameter vector β is common for all choices, whereas the covariates vary by choice.
Here, i indicates firms. The dependent variable is the extensive margin and is a dummy variable. The dummy variable equals 1 if the firm reported positive R&D expense in the corresponding year and 0 otherwise. The main variable of interest, $CCExposure_{i,t}$ is the firm-level climate change exposure

[5] The conditional MLE in the unobserved effects logit model relies on the premise of conditional independence (CI), which implies that binary responses are independent over time, given observed variables and unobserved heterogeneity.

constructed by Sautner et al. (2023). For the purpose of this study, I report the marginal effects and the standard errors.

3.3. Measurements of variables

To test the hypotheses regarding how climate change exposure affects intensive margins of R&D investment, I use intensive and extensive margins of R&D as the dependent variables. The intensive margin of R&D is how much to invest in R&D in the business. The intensive margin of R&D is defined as the total expenditure in R&D over the number of firms engaged in R&D activities. Using Compustat data, one concern pertains to potential selectivity issues arising from firms with zero R&D investment. Moreover, a zero R&D ratio in a specific year for some firms may be due to substantial past or planned future investments. Hence, a zero value does not signify a significant behavioral difference regarding innovation. There are 4178 missing firm observations for R&D and 7699 firm observations with zero R&D. I follow the R&D investment literature (Banerjee & Gupta, 2021; Sunder et al., 2017; Wang et al., 2022 Lin et al., 2011; Czarnitzki & Toole, 2008) and set the missing R&D expenses to zero. Following previous literature Yeh et al. (2010) and Hoang (2022), I construct intensive margins of R&D as positive values of R&D expenditure divided by total sales. Analyzing intensive margins helps understand how much emphasis and investment are given to R&D spending. Other alternative measures are R&D expenditure (R&D divided by assets, R&D divided by number of employees and average R&D), which are used in the robustness tests.

An extensive margin is the increase in R&D expenditure captured by the number of firms that begin performing R&D. Also, the extensive margin is the firm's decision to invest or not. This is based on firms that reported positive R&D and firms that report zero R&D and having missing R&D. I construct the extensive margin, dependent variable, as a dummy variable, and it is set to 1 if the firm reports a positive R&D spend in a given year, and 0 otherwise[6].

The main variable of interest is firm-level climate change. I utilize data developed by Saunter et al. (2023) to assess the extent of climate change exposure at the firm level[7]. These researchers create dynamic indicators of climate change exposure by analyzing earnings conference call transcripts. They employ a machine learning algorithm to generate sets of climate change-related word pairs (referred to as "bigrams") and gauge the frequency of these bigrams in the transcripts, normalized by the total number of bigrams. Essentially, this measurement reflects the presence of climate change-related events or disruptions specific to each firm. In their study, they demonstrate how these climate exposure measures effectively capture firm-level vulnerabilities associated with both the physical and regulatory impacts of climate change. This measure captures the market's assessment of the exposure of a firm to numerous upside and downside climate change aspects, including physical dangers, regulatory actions, and technology opportunities.

Following other research (Barnerjee & Gupta (2021), I control for firm factors that have been shown to impact R&D margins significantly. Firm size is the natural logarithm of the book value of total assets. Firm age is the difference between the year under investigation and the year when the

[6] A limitation to this study comparing firms with missing R&D versus those with zero or positive R&D might be challenging due to non-random selection.

[7] The COMPUSTAT data is a long panel which contains a large set of firms from various industries. This helps to examine firm-level heterogeneity and allows to exploit individual fixed effects.

company's data became available in Compustat and CRSP datasets. As a result, firm age proxies' experience and R&D activities may benefit or be detrimental to organizational aging. Market-to-book is the ratio of asset market value to asset book value. The market-to-book ratio is included because higher earnings are directed toward R&D investments if a firm is innovative. Capital investment is corporate capital expenditure divided by total asset book value. Cash holding (cash hold) is measured as cash scaled by the value of total assets. Total debt is the sum of long-term debt and debt in current liabilities scaled by total assets. I include total debt to capture how the capital structure of the firm and its internal financing decisions affect R&D margins. Industry Sales growth (sales growth) is the % age of sales (sale) growth from the previous year to the current year by 2-digit industry. A dividend dummy indicates 1 if firms pay dividends to common shareholders and 0 if they do not. Profitability (ROA) is pretax income scaled by total assets. I lag explanatory variables by one period to avoid simultaneity and reverse causality problems (see Mairesse and Mohnen, 2010).

The variable descriptions are found in Appendix A.

4. Discussion of results

The summary statistics are presented in Table 1. I measure the intensive margin of R&D investment as R&D expenditure scaled by total assets. On average, firms spend about $167.27 million on R&D. Firms spend. The mean of intensive margin of R&D is 3.2% with a standard deviation of 6.67%. The average value of the intensive margin of R&D is significantly higher than its median value. This implies that many firms spend less (or nothing) on R&D and there is a significant variance in the measure of climate change exposures. On average, firms spend 5.5% of their total assets on R&D investment. Firm-level climate change exposure has a mean of 0.0009 (0.9%) and a standard deviation of 0.0023 (0.23%). The values for the climate change exposure values are slightly lower than those in Sautner et al. (2023), who examined data from 10,673 companies in 34 nations. The correlation matrix in Table 2 provides early evidence that the intensive margin of R&D investment is positively correlated with firm-level climate change.

This supports hypothesis 1b, which states that climate change exposure increases the extensive and intensive margin of R&D investment based on the strategic growth options theory. Firm size and age are negatively correlated with the intensive margin of corporate R&D. The result is that larger and older firms tend to invest less in R&D. Larger and older firms may invest less in R&D due to a preference for stability, profitability from existing products, potential difficulties in adjusting to innovative changes and other industry conditions.

4.1. Major regression results

Table 4 presents the regression results where the dependent variable is the intensive margin of R&D (R&D divided by total assets). In column (1), I conduct univariate regression without adding any control variables, the coefficient is significantly positive at a 1% significant level. For economic significance, one standard deviation increase in climate change exposure leads to a 3.32% increase in the intensive margin of corporate R&D investment[8]. In column 2, the estimated coefficient is positive

[8] I compute the estimated economic effect by multiplying the climate change exposure coefficient (0.9641) by the standard deviation of climate change exposure (0.0023) and dividing it by the mean of the R&D intensive (0.055).

and statistically significant at 5%. The economic effect is that one standard deviation increase in climate change exposure increases the intensive margin of R&D by 1.50% %when I include firm-level characteristics with year and firm-fixed effects. This result is consistent with hypothesis 1b, which suggests that climate change exposure increases the intensive margin of R&D investment based on the strategic growth options theory (Vo & Le, 2017). In column 3, I use the industry-intensive margin of R&D as the dependent variable. The effect of climate change exposure on firms' intensive margin of R&D investment is significantly positive at a 5% significance level. The positive effect of climate change exposure increases more on the industry-intensive margin of R&D when industry and year-fixed effects are accounted for. The results reveal a statistically and economically significant relationship between climate change exposure and R&D investment. Specifically, a one standard deviation increase in climate change exposure leads to a 5.15% rise in the intensive margin of R&D investment, as shown in the full model. This suggests that firms facing higher climate risks intensify their R&D efforts, likely to mitigate climate-related challenges or seize emerging opportunities. Economically, this aligns with the theory of strategic growth options, where uncertainty drives firms to invest in innovation to maintain competitiveness. Such investments can lead to sustainable technologies and climate-resilient solutions, benefiting both firms and society.

From a policy perspective, these findings emphasize the need for supportive measures to encourage R&D in climate-vulnerable sectors. Policies such as R&D tax incentives, funding for climate-related research, and clear regulatory frameworks can reduce uncertainty and foster innovation. By aligning climate and innovation policies, governments can accelerate the transition to a low-carbon economy while enhancing economic resilience. Overall, the results highlight climate change as both a challenge and an opportunity, providing strong theoretical support for policies that promote innovation as a strategic response to climate risk exposure.

The positive coefficient for cash holding suggests that firms with higher cash reserves tend to invest more in R&D. This suggests that financial flexibility enables firms to devote resources to innovation. Profitability exhibits a negative relationship with an intensive margin of R&D. This indicates that more profitable firms may allocate fewer resources to R&D spending.

I examine the effects of climate change exposure on the intensive margin of corporate R&D investment.

Table 2. Summary statistics.

The summary statistics for the variables in this paper are shown in table 2. I present the mean, standard deviation, and the various percentile distributions. Financial firms (SIC 6000-6999) and utility firms (SIC 4900- 4999) were excluded from the analysis. I winsorize all continuous variables between the 1% and 99% percentiles. The sample data includes public firms in United States obtained from Compustat from 2002 to 2022. The Appendix A contains a detailed set of variable definitions.

	N	Mean	Std. Dev.	p25	P50	p75	p99
Panel A: Variable of interest							
Dependent variables							
Positive R&D (millions of dollars)	24923	167.277	936.8362	0	0.43	25.985	4566
R&D intensive margin (R&D/ total assets)	24923	0.055	0.4714	0	0.0025	0.0415	0.4215
R&D intensive margin (R&D/ total sales)	24923	0.0322	0.0667	0	0.0026	0.036	0.2869
R&D extensive (1=engage and 0 otherwise)	24923	0.8554	0.3517	0	1	1	1
Climate related variables							
Climate change exposure	24923	0.0009	0.0023	0.0001	0.0003	0.0007	0.0117
Opportunity exposure	24923	0.0002	0.0010	0	0	0.0001	0.0047
Regulatory exposure	24923	0.0001	0.0002	0	0	0	0.0009
Physical exposure	24923	0.0003	0.0001	0	0	0	0.0003
Firm-specific variables							
Firm size	24923	6.6805	2.2495	5.0854	6.7523	8.2318	11.7389
Firm age	24923	30.9538	9.9642	15	20	37	70
Total debt	24923	0.1661	0.1618	0.0324	0.1273	0.2466	0.6846
Cash holding	24923	0.1188	0.1262	0.0305	0.0784	0.1619	0.6032
Dividend dummy	24923	0.4578	0.4982	0	0	1	1
Profitability	24923	0.0968	0.2126	0.0633	0.1137	0.1655	0.3776
Tobin Q	24923	1.6473	1.6233	0.8357	1.2081	1.8934	7.926
Book to market ratio	24923	0.0008	0.1581	0	0	0.0001	0.0003
Capital investment	24923	0.2199	0.2336	0.1116	0.1766	0.278	0.7864
Industry Controls							
Industry sales growth	24923	0.2802	14.0722	−0.0256	0.0603	0.1627	1.2956
Lerner index (Market power)	24923	0.0506	2.0989	0.0515	0.113	0.191	0.5987
Panel B: Macroeconomic Controls							
Inflation	21	2.43333	1.73590	1.6	2.1	3.2	8
Interest Rate	21	1.38524	1.67559	0.12	0.54	2.16	5.24
Real GDP	21	9.72044	0.11426	9.64077	9.69892	9.81522	9.91257
Global Fin. Crisis (2007–2009)	21	0.14286	0.35857	0	0	0	1

Table 3. Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) R&D intensive	1.000										
(2) Climate change exposure	0.012	1.000									
(4) Firm size	–0.160	–0.044	0.021	1.000							
(5) Firm age	–0.146	–0.035	0.033	0.140	1.000						
(6) Total debt	–0.127	–0.001	–0.050	0.210	0.083	1.000					
(7) cash holding	0.390	0.040	–0.008	–0.279	–0.193	–0.339	1.000				
(8) Profitability	–0.344	–0.033	–0.006	0.295	0.114	–0.023	–0.215	1.000			
(9) Tobin Q	0.214	0.025	–0.013	–0.081	–0.209	–0.269	0.272	–0.202	1.000		
(10) Book to market ratio	0.002	0.002	–0.002	–0.001	–0.006	–0.026	0.001	–0.002	0.005	1.000	
(11) Market power	–0.266	0.000	–0.006	0.090	0.030	0.021	–0.111	0.378	–0.138	0.000	1.000

This table reports correlation analysis. Definitions of variables are found in Appendix A. The sample period is 2002–2022.

Table 4. Firm-level climate change exposure and R&D intensive margins.

This table presents fixed effects estimate of the effects of climate change exposure (CCE) on corporate R&D intensive margins using R&D/total sale as the dependent variable. Model 1 reports estimate using the CCE measure of climate change without any controls. Model 2 reports the estimates of how CCE affects R&D intensive margins after controlling for year, and firm fixed effect. Model 3 result shows how CCE affects R&D intensive margins at the industry level (2-digit SIC industry) when year effects industry fixed effects and firm-level characteristics are included. Column (4) and model 4 includes year, firm, industry effects, firm, industry, and macroeconomic controls. Appendix A presents variable definitions. Standard errors are clustered at the firm level. Standard errors are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)
			Industry	
	R&D	R&D	R&D	R&D
climate change expo	0.9641***	0.436**	30.5018***	1.4942**
	(0.2295)	(0.1741)	(7.6231)	(0.5939)
Firm size		0.005***	0.9358***	0.0078***
		(0.0006)	(0.0183)	(0.0011)
Total debt		–0.0661***	–1.755***	–0.057***
		(0.0053)	(0.2209)	(0.0148)
Firm age		–0.0005***	0.0027*	–0.0008***
		(0.0001)	(0.0014)	(0.0001)
Cash holding		0.2019***	0.8884***	0.2925***
		(0.0189)	(0.1756)	(0.0497)
Dividend dummy		–0.0259***	–0.4106***	–0.0386***
		(0.0015)	(0.0278)	(0.0024)
Profitability		–0.1332***	–0.537***	0.1774***
		(0.034)	(0.1203)	(0.0594)
Tobin Q		0.0093***	0.0131	0.0044
		(0.0023)	(0.0173)	(0.0048)
Book to market ratio		–0.0005*	–0.1816***	0.0012***
		(0.0003)	(0.0414)	(0.0004)
Capital investment		0.0065	0.4249	–0.0181
		(0.0045)	(0.2934)	(0.0215)
Sale growth			–0.0092***	–3.61e–06
			(0.0029)	(0.0002)
Lerner			0.0004	–0.1845***
			(0.0035)	(0.0221)
Inflation				0.0011
				(0.0007)
Federal interest rate				0.0026***
				(0.0005)
Global Financial Crisis				0.0167***
				(0.0039)
Global financial crisis				–0.0182
				(0.0135)
Constant	0.037***	0.0182***	–5.7392***	0.1727
	(0.0002)	(0.0065)	(0.3276)	(0.1248)
Observations	24923	24923	11650	24923
R-squared	0.0016	0.2252	0.7128	0.6596
Year Effects	Yes	Yes	Yes	Yes
Firm Effects	No	No	No	Yes
Industry Effects	No	No	Yes	Yes

Potential Mechanism

The interaction effects of how climate change exposure affects the intensive margin of R&D

Climate change exposure influences the intensive margin of R&D through several economic channels, including vertical integration and growth opportunities, as demonstrated in Table 5. In Model 1, the interaction between climate change exposure and vertical integration yields a coefficient of 1.7882, significant at the 1% level. This indicates that vertically integrated firms are better equipped to leverage their internal capabilities to respond to climate change, thereby increasing R&D intensity. This supports Hypothesis 2, which posits a positive relationship between vertical integration, climate change exposure, and R&D investment. Vertically integrated firms can more effectively align their operations with climate policies, innovate efficiently, and mitigate risks, leading to higher R&D spending.

In Model 2, the interaction term between climate change exposure and growth opportunities has a coefficient of 0.4809, significant at the 5% level. This suggests that firms with greater growth opportunities are more likely to intensify R&D efforts in response to climate risks, supporting Hypothesis 3. Firms perceiving climate change as a source of strategic growth are incentivized to invest in innovation to capture emerging markets, develop sustainable technologies, and enhance competitiveness.

From a policy perspective, these mechanisms highlight the importance of fostering vertical integration and growth opportunities to amplify R&D responses to climate change. Policies that encourage supply chain consolidation, provide incentives for sustainable innovation, and support market expansion can enhance firms' ability to invest in R&D. By creating an enabling environment for innovation, policymakers can strengthen corporate resilience to climate risks while driving the transition to a low-carbon economy. These findings underscore the dual role of climate change as both a challenge and an opportunity, offering a robust rationale for policies that promote R&D as a strategic response to climate risk exposure.

The sub-sample analysis of carbon-intensive and green firms, as well as manufacturing and non-manufacturing firms, reveals that climate change exposure has a more pronounced effect on the intensive margin of corporate R&D investment for firms in carbon-intensive industries compared to those in green industries. This finding suggests that carbon-intensive firms, which are inherently more vulnerable to regulatory and physical risks associated with climate change, are compelled to allocate greater resources to R&D to mitigate these risks and adapt to evolving environmental standards. The heightened R&D investment in carbon-intensive industries can be attributed to the urgent need to develop technologies that reduce carbon emissions, improve energy efficiency, and transition toward sustainable practices. These firms face mounting pressure from stakeholders, including regulators, investors, and consumers, to align their operations with climate goals, thereby driving innovation as a strategic response to maintain competitiveness and ensure long-term viability.

Similarly, the analysis between manufacturing and non-manufacturing firms indicates that manufacturing firms, which are often more exposed to climate change risks due to their reliance on energy-intensive processes and supply chains, tend to invest significantly more in the intensive margin of R&D than non-manufacturing firms. Manufacturing firms are typically at the forefront of industrial emissions and resource consumption, making them primary targets for climate-related regulations. Consequently, these firms are incentivized to innovate to comply with stricter emissions standards, reduce operational costs, and capitalize on emerging market opportunities for green technologies. The higher R&D investment in manufacturing firms reflects their proactive approach to addressing climate change challenges through technological advancements and process improvements.

These findings align with Hypothesis 4, which posits that the intensive margins of R&D investment increase for carbon-intensive and manufacturing firms as climate change exposures intensify. The results underscore the critical role of tailored regulatory frameworks in fostering climate-resilient innovation. From a policy perspective, it is imperative to design targeted incentives that encourage carbon-intensive and manufacturing firms to amplify their R&D efforts. Mechanisms such as tax credits for green innovation, subsidies for the development and deployment of climate-resilient technologies, and stricter emissions standards coupled with financial incentives for compliance can serve as effective tools to drive innovation. Such policies not only promote sustainable practices but also ensure that these sectors remain competitive and contribute meaningfully to the global climate change agenda. By addressing the unique challenges faced by carbon-intensive and manufacturing firms, policymakers can facilitate a transition toward a low-carbon economy while supporting economic growth and technological progress.

Climate change exposure and the extensive margin of R&D

I examine the effects of climate change exposure on extensive margin of R&D. Without any controls, the result in Table 7 shows that climate change exposure affects extensive margin of R&D positively. The probability of engaging in R&D is 16.56%, statistically significant at 5% in column 1. In column 3, the extensive margin of R&D increases by 16.11% when firm and macroeconomic controls are included.

I further test whether the extensive margin of R&D effect is stronger for carbon-intensive firms when climate change exposure increases. The result shows that the extensive margin of R&D increases by 24.23% for firms in carbon-intensive industries when climate change exposure increases compared to green firms' 10.16%. This finding supports the interpretation that climate change exposure improves firms' incentives to engage in R&D, which is consistent with the strategic growth option theory.

Table 5. Channels through which Firm-level climate change exposure and R&D intensive margins.

This table presents fixed effects estimate of the effects of climate change exposure (CCE) on intensive margins of corporate R&D using R&D/total sale as the dependent variable. This examines the potential channels through which climate change exposure affects intensive margin of corporate R&D. Appendix A presents variable definitions. The sample comprises 2296 firms in the COMPUSTAT data from 2002- 2022, excluding financial firms (SIC 6000-6999) and utility firms (SIC 4900-4999). Standard errors are clustered at the firm level. Standard errors are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)
	R&D	R&D
Climate Change exposure	0.7913***	0.4902**
	(0.1976)	(0.2371)
Vertical integration	0.0373***	
	(0.0075)	
CC exposure x integration	1.7882***	
	(0.3057)	
Growth opportunities		0.0087***
		(0.0032)
CC exposure x growth		0.4809**
		(0.2447)
Firm size	−0.0013***	−0.0011***
	(0.0003)	(0.0002)
Firm age	−0.0033***	−0.0054***
	(0.0008)	(0.0004)
Total debt	−0.0001***	−0.0002***
	(0.0001)	(0.0001)
Cash holding	0.108***	0.1197***
	(0.0076)	(0.0084)
Dividend dummy	−0.0109***	−0.0096***
	(0.001)	(0.0005)
Profitability	−0.0668***	−0.0425***
	(0.0194)	(0.0125)
Tobin Q	0.0052***	−0.0021
	(0.0009)	(0.0032)
Book to market ratio	−0.0011***	−0.0007***
	(0.0002)	(0.0002)
Capital investment	0.0119**	0.0077**
	(0.0049)	(0.0035)
Constant	0.2562***	0.2362***
	(0.0388)	(0.0272)
Observations	24923	21238
R−squared	0.3021	0.2405
Year Effects	Yes	Yes
Firm Effects	Yes	Yes
Industry Effects	Yes	Yes
Other Controls	Yes	Yes

Table 6. Firm-level climate change exposure and R&D intensive margins across the industry.

This table presents fixed effects estimate of the effects of climate change exposure (CCE) on corporate R&D intensive margins using R&D/total sale as the dependent variable. Model 1 and 2 reports the estimates of how CCE affects R&D intensive margins among carbon intensity firms (firms that emits high carbons) and green firms after controlling for year, firm, industry effects as well as firm, industry and macroeconomic. Columns (3-4) show estimates among manufacturing and non-manufacturing firms when year, firm, industry effects as well as firm, industry and macroeconomic controls are included. Appendix A presents variable definitions. The sample comprises 2296 firms in the COMPUSTAT data from 2002-2022. Standard errors are clustered at the firm level. Standard errors are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	(1) Carbon intensity firms	(2) Green firms	(3) Manufacturing firms	(4) Non-manufacturing firms
Dependent: Intensive margin				
climate change expo	7.4232**	0.5531*	2.4082**	0.8735
	(3.5261)	(0.2400)	(1.3103)	(0.1973)
Firm size	0.0128***	0.0066***	0.0111***	0.0042***
	(0.0023)	(0.0010)	(0.0018)	(0.0006)
Total debt	−0.0484	−0.0772***	−0.0585**	−0.0464***
	(0.0644)	(0.0110)	(0.0269)	(0.0062)
Firm age	−0.0015***	−0.0007***	−0.0007**	−0.0012***
	(0.0005)	(0.0003)	(0.0003)	(0.0002)
Cashholding	0.6327***	0.1724***	0.3955***	0.1378***
	(0.1449)	(0.0400)	(0.0824)	(0.0164)
Dividend dummy	−0.0545***	−0.0306***	−0.0573***	−0.0197***
	(0.0072)	(0.0035)	(0.0032)	(0.0014)
Profitability	0.2652**	0.0946	0.1987**	0.0259
	(0.1068)	(0.0794)	(0.0811)	(0.0477)
Tobin Q	−0.0100	0.009***	0.0008	0.0078***
	(0.0194)	(0.003)	(0.0077)	(0.0011)
Book to market ratio	−0.0003	0.0007	0.0022*	0.0008**
	(0.0170)	(0.0009)	(0.0013)	(0.0004)
Capital investment	0.0156	−0.0358	0.0118	−0.0056
	(0.0190)	(0.0364)	(0.0192)	(0.0245)
Sale growth	0.0002	−0.0004	−0.0047	−0.0001
	(0.0001)	(0.0005)	(0.006)	(0.0001)
Lerner	−0.1988***	−0.1819***	−0.1884***	−0.0772*
	(0.0499)	(0.0212)	(0.0213)	(0.0427)
Inflation	0.0021	0.0007	0.0001	0.0019***
	(0.0015)	(0.0008)	(0.0007)	(0.0006)
Federal interest rate	0.0028***	0.0026***	0.0044***	−0.0001
	(0.0010)	(0.0006)	(0.0010)	(0.0003)
Global Financial Crisis	0.0478***	0.0032*	0.0227***	0.0034**
	(0.0150)	(0.0019)	(0.0075)	(0.0015)
Real GDP	−0.0626***	−0.0082	−0.0275*	0.0012
	(0.0195)	(0.0163)	(0.0162)	(0.0121)
Constant	0.5708***	0.0988	0.2483*	0.0079
	(0.1662)	(0.1570)	(0.1421)	(0.1198)
Observations	6535	18388	14335	10588
R−Squared	0.3697	0.7846	0.6746	0.3750
Year Effects	Yes	Yes	Yes	Yes
Firm Effects	Yes	Yes	Yes	Yes
Industry Effects	Yes	Yes	Yes	Yes

Table 7. Firm-level climate change exposure and R&D extensive margins.

This table reports the regression results estimating Equation (1). All the variables are defined in Appendix A. I estimate conditional logistic regressions when the R&D measure is a binary variable. Robust standard errors are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(3)
Dependent: R&D Extensive	Marginal Effects	Marginal Effects
climate change expo	0.16557***	0.1611*
	(0.1049)	(0.1038)
Firm size		0.0297***
		(0.0011)
Total debt		0.0267***
		(0.0148)
Firm age		0.0293***
		(0.0219)
Cash holding		0.0345***
		(0.0497)
Dividend dummy		0.0087*
		(0.0024)
Profitability		0.0263***
		(0.0018)
Tobin Q		0.0036**
		(0.0018)
Book to market ratio		0.0064
		(0.0167)
Capital investment		-0.0181
		(0.0215)
Sale growth		0.0293
		(0.0002)
Lerner		0.0025**
		(0.0010)
Inflation		0.0015
		(0.0051)
Federal interest rate		0.0091
		(0.0074)
Global Financial Crisis		0.0019
		(0.0039)
Real GDP		0.0288
		(0.0454)
Observations	24923	24923
Pseudo R-Squared	0.0001	0.0187
Year Effects	Yes	Yes
Firm Effects	No	Yes
Industry Effects	No	Yes

Table 8. Firm-level climate change exposure and R&D extensive margins.

This table presents regression results on a subsample of firms in carbon intensive and green industry. high corrupt and low corrupt states. The dependent variable is extensive margin of R&D (R&D measure is a binary). All the firm controls from the baseline model are included in the regression. All the firm variables are winsorized at 1% and these are defined in Appendix A. Standard errors are clustered at firm level. *, **, *** indicates statistical significance at the 10%, 5%, and 1% level, respectively.

	Carbon intensive firms	Green firms	Manufacturing firms	Non-manu facturing firms
Dependent: R&D Extensive	Marginal Effects	Marginal Effects	Marginal Effects	Marginal Effects
climate change expo	0.2423**	0.1016*	0.3486**	0.4141
	(0.0230)	(0.1239)	(0.674)	(0.3735)
Firm size	0.0043**	0.0157***	0.0294***	0.0194***
	(0.0017)	(0.0020)	(0.0023)	(0.0012)
Total debt	0.0179	0.1142***	0.0899**	0.0378***
	(0.0231)	(0.0210)	(0.0284)	(0.0106)
Firm age	0.0007**	0.0013***	0.0015***	0.0010***
	(0.0003)	(0.0003)	(0.0004)	(0.0002)
Cash holding	0.1063***	0.2840***	0.4422***	0.0339***
	(0.0259)	(0.0387)	(0.0442)	(0.0101)
Dividend dummy	0.0132**	0.0164**	0.0397***	0.0217***
	(0.0078)	(0.0066)	(0.0099)	(0.0042)
Profitability	0.0297**	0.2428***	0.5746***	0.0163**
	(0.0127)	(0.0351)	(0.0500)	(0.0060)
Tobin Q	0.0089**	0.0008	0.0086**	0.0005
	(0.0028)	(0.0022)	(0.0039)	(0.0006)
Book to market ratio	0.0097	0.0059	0.1818	0.0313
	(0.0828)	(0.0177)	(0.1584)	(0.0217)
Capital investment	0.0205	0.1215***	0.4603***	0.0019
	(0.0206)	(0.0225)	(0.0313)	(0.0058)
Sale growth	0.0003	0.0011***	0.0022***	0.0001
	(0.0009)	(0.0003)	(0.0004)	(0.003)
Lerner	0.0056	0.0040***	0.1906**	0.001
	(0.0041)	(0.0012)	(0.0240)	(0.002)
Observations	6,530	18,373	14,322	10,581
Pseudo R-Squared	0.0263	0.0282	0.1977	0.0548
Year Effects	Yes	Yes	Yes	Yes
Firm Effects	No	No	Yes	Yes
Industry Effects	No	No	Yes	Yes
Other controls	No	No	Yes	Yes

Event Study Based on Different Time Events of Paris Agreement

Paris Agreement

I use the different time events for Paris Agreement to estimate treatment effects depending on intensive margin of R&D. The Paris Agreement is a climate change adaptation and mitigation accord inside the United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement is a legally enforceable international climate change treaty design by United Nations. It was adopted by 198 parties on 12 December 2015 and went into effect on November 4, 2016. Its goal is to keep global warming below 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to pre-industrial levels. As a result, I purposefully choose this shock with a large worldwide impact to make comparisons across time. The Paris Agreement raises climate change regulatory exposure and may push firms with high climate change risk or those in climate-sensitive industries to spend more on environmentally friendly initiatives.

I conduct an event study using treatment effects at different time periods from when the program was received: 1= during the adoption of Paris Accord (2015–2016) and 0 otherwise; 1 = announcement of withdrawal from the Paris Accord (2017–2020), 0 Otherwise and 1=rejoining the Paris Accord and 0 Otherwise. The main aim of this test is to show that firms' intensive margin of R&D is influenced by climate change exposure under different time periods of Paris Agreement. I estimate the following regression model to examine the impact s climate change exposures on the intensive margin of corporate R&D:

$$R\&D\_int_{it} = \alpha + \beta_1 CCExposure_{i,t} + \beta_2 time_{Paris\ Agreement_t} + \beta_3 CCExposure_{i,t} * time_{Paris\ Agreement_t} + \sum \beta_{k,j} X_{k,j,t-1} + \delta_t + \varpi_i + \varepsilon_{i,t} \quad (3)$$

where i and t index firm and year, respectively. The dependent variable *CSR* represents the corporate social responsibility score of firm i at time t. The variable of interest is the interaction term $CCExposure \times time_{Paris\ Agreement_t}$. The $time_{Paris\ Agreement_t}$ is U.S. Paris Agreement Participation Phases. Paris Adoption (2015–2016): This phase captures the adoption of the Paris Agreement. During this period, the U.S. signed and ratified the agreement, committing to climate change mitigation efforts. Paris adoption = 1 for the adoption period, 0 otherwise.

Paris Withdrawal (2017–2020): This period marks the announcement and withdrawal from the Paris Agreement. In this phase, U.S. policy shifted toward disengagement from the accord. Paris Accord withdrawal = 1 for the withdrawal period, 0 otherwise.

Paris Rejoin (2021 onward): This final phase captures the rejoining of the Paris Agreement. After reentering in 2021, the U.S. renewed its commitment to global climate action. Paris Accord Rejoin = 1 for the rejoining period, 0 otherwise.*CC Exposure* is the firm-level climate change risk index in year t. $X_{k,j,t-1}$ are the firm-level, industry, and macroeconomic control variables. The interaction term's coefficient, β_3, captures the influence of the Paris Agreement on firms' amount spent on R&D in those years.

The interaction term coefficient is positive and statistically significant at the 5% level when the US joined the Paris Accord. This shows that the positive impact of climate change exposure on intensive margin of R&D increase during the Paris Accord adoption period. Moreover, the negative interaction effect (−1.4382 and −1.6443 in models 1 and 2) suggests that climate change exposure had a negative impact on the intensive margin of R&D during the withdrawal period. Uncertainty about future laws and incentives may have led firms to limit their R&D investments in climate-related technologies, preferring to wait for more stable policy signals. In models 1 and 2, the estimated coefficients (1.2855 and 2.8295 in models 1 and 2) are positive and statistically significant at the 5% level. This shows a strong positive interaction effect, indicating that the rejoining of the Paris Accord significantly enhanced the positive impact of climate change exposure on the intensive margin of R&D.

Table 9. Firm-level climate change exposure and intensive margin of R&D.

This table reports the regression results estimating Equation (3). All the variables are defined in Appendix A. I estimate the fixed regressions for the effects of different time periods of Paris Accord on intensive R&D measure. Robust standard errors are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

	Model 1	Model 2
climate change exposure	2.4876**	2.3717**
	(1.0788)	(0.9881)
Events:		
Paris Accord adoption (2015-2016)	0.0107***	0.0118***
	(0.0009)	(0.0027)
Paris Accord withdrawal (2017-2020)	−0.0022	−0.0230
	(0.0009)	(0.0047)
Paris Accord adoption x CC exposure	2.3115**	2.0439**
	(1.1504)	(1.0722)
Paris Accord withdrawal x CC exposure	−1.4382*	−1.6443*
	(1.0900)	(0.9468)
Firm size		0.0039***
		(0.0011)
Total debt		−0.0281***
		(0.0023)
Firm age		− 0.0007***
		(0.0001)
Cash holding		0.2922***
		(0.0488)
Dividend dummy		−0.0314***
		(0.0027)
Profitability		0.1664**
		(0.0566)
Tobin Q		0.0052
		(0.0047)
Sale growth		0.0001
		(0.0002)
Observations	24,923	24,923
R-Squared	0.001	0.6619
Year Effects	Yes	Yes
Firm Effects	No	Yes
Industry Effects	No	Yes
Controls	No	Yes

A quasi-natural experiment based on the RPS

To identify the causal effect of climate change exposure on the intensive margin of R&D, I focus on the Renewable Portfolio Standard and use a difference-in-indifferences (DiD) research design to examine the impacts of this policy on the intensive margin of corporate R&D.

Renewable Portfolio Standard

The United States, through Members of Congress, have varied perspectives on climate change, propose measures like carbon pricing, clean energy standards, and GHG-abating technology funding. Some resolutions oppose multisector carbon pricing for economic reasons. Votes on comprehensive climate policy are rare, but enacted laws include renewable energy tax incentives and carbon capture efforts (Congressional Research Service report,2021). RPS are one of these policies, which require that a particular % age of a state's power supply be generated from renewable sources, have been a major exception. The first RPS was enacted in Iowa in 1991, and others have since followed suit. I concentrate on the impact of RPS, which is extensively employed as substantive state-level climate policy (Rabe, 2006). RPS requires electricity retailers to supply a particular % age of renewable energy to increase renewable energy supply (Lee, 2020). RPS regulations were enacted in 29 states and the District of Columbia as of 2015, accounting for 62% of total electricity generation[9].

However, 18 States continue to adopt RPS after 2015. Thus, they are the treatment group, and the treatment period of interest is 2015 and beyond, as shown in Figure 4 and Table 10A.

I use differences in different research designs based on states that adopt RPS programs (Treated States) and the non-adoption States (Control States). I control for other covariates that could influence changes in intensive margin of R&D:

$$R\&D\_int_i = \alpha + \beta_1 Post\_year_i + \beta_2 RPS\ State_i + \beta_3 Post\_year_i * RPS\ State_i + \sum \beta_{k,j} X_{k,j,t-1} + \delta_t + \varpi_i + \varepsilon_{i,t} \quad (4)$$

where i and t index firm and year, respectively. The dependent variable $\&D\_int$ represents the intensive margin of R&D of firm i at time t. $Post\_year_{i,t}$ is treatment period of interest is 2015 and beyond. $RPS\ State$ is a dummy variable that equals 1 for a firm in the State adopting RPS after 2016 (defined as treatment firms) and zero for non-adopting States (control firms). The variable of interest is the interaction term $Post\_year_i * RPS\ State_i$. *CCExposure* is the firm-level climate change risk index in year t. $X_{k,j,t-1}$ are the firm-level, industry and macroeconomic control variables. The interaction term's coefficient, β_3, captures the influence of the RPS on firms' amount spend on R&D in those years. I expect a positive and statistically significant coefficient of the interaction term between climate change exposure and the Paris Agreement. Before running the analysis, I tested for the parallel trend assumption.

[9] Renewable Portfolio Standards (RPS) demand that utilities sell a certain amount of their electricity from renewable sources. States established these requirements to diversify their energy resources, foster domestic energy generation, and promote economic development.

Table 10A. States that adopted and did not adopt RPS after the Paris Agreement.

Treated States	Control States
Illinois	Alabama
Massachusetts	Alaska
Michigan	Arizona
New York	Arkansas
Oregon	Delaware
Rhode Island	Florida
Connecticut	Georgia
Maryland	Hawaii
Maine	Idaho
New Hampshire	Indiana
Pennsylvania	Iowa
California	Kansas
New Jersey	Kentucky
Colorado	Louisiana
New Mexico	Minnesota
Nevada	Mississippi
Ohio	Missouri
Washington	Montana
	Nebraska
	North Carolina
	North Dakota
	Oklahoma
	South Carolina
	South Dakota
	Tennessee
	Texas
	Utah
	Vermont
	Virginia
	West Virginia
	Wisconsin
	Wyoming

Parallel Trend Assumption

I demonstrate and confirm the parallel trends assumption in Figure 4, which posits that the pre-intervention trends in the outcome variable are consistent between the treatment and control groups. This assumption necessitates that, in the absence of policy intervention, the difference in the outcome variable remains constant between the treatment group and the control group. In Figure 4, both groups' intensive margin of R&D displays similar trends. This shows that the parallel trends assumption is satisfied.

In Table 10B, I conduct a preliminary analysis of the treatment effects of the outcome variable (intensive margin of R&D). I compute average intensive margin of R&D for pre-policy and post-policy periods. Applying the difference-in-difference, my result shows a positive effect and a statistically significant increase in intensive margin of R&D by 0.023. The analysis of the treatment effects of other covariates is shown in Table 10C.

Table 12 provides insights into the effect of RPS treated states and post year periods on intensive margin of R&D, considering climate change exposure as a moderating factor. In column 1, the interaction term "Post period x CC exposure" is positive and statistically significant at 10%, suggesting that the post-policy period further enhances the impact of climate change exposure on intensive margin of R&D corporate investment. Furthermore, in column 2, the interaction term "RPS Treated x CC exposure" is positive and significant, implying that RPS treatment combined with climate change exposure leads to increased intensive margin of R&D corporate investment.

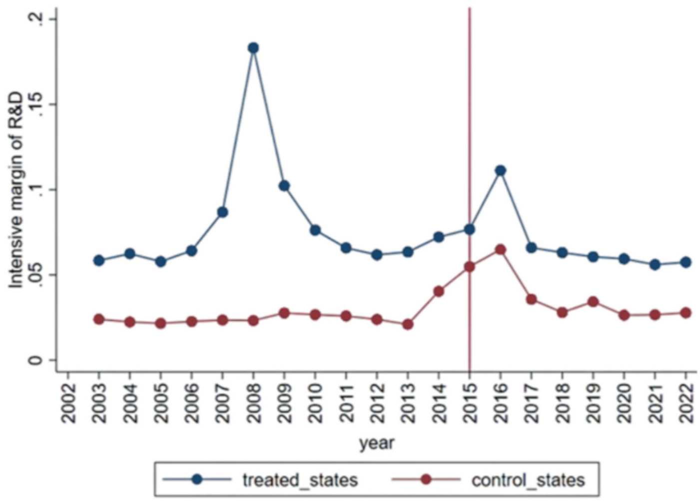

Figure 4. Trend of intensive margin of R&D between the "Treated States" vs "Control States".

Table 10B. Preliminary analysis of treatment effects value in parenthesis is the standard error for treatment effects.

	Treatment Group	Control Group	Treatment Effect
Post	0.079	0.025	0.054
Pre	0.070	0.039	0.031
DID Estimator	0.009	−0.014	**0.023**** **(0.013)**

Table 10C. Analysis of treatment effects.

Variable(s)	Mean Control	Mean Treated	Diff.	P-value
climate change expo	0.001	0.002	0.001	0.018**
Firm size	6.445	6.338	−0.107	0.002***
Total debt	1.206	1.099	−0.107	0.000***
Firm age	31.366	31.29	−0.077	0.588
Cash holding	0.099	0.134	0.035	0.000***
Dividend dummy	0.471	0.418	−0.053	0.000***
Profitability	0.113	0.09	−0.023	0.000***
Tobin Q	1.45	1.593	0.143	0.000***
Book to market ratio	0.004	−0.001	−0.004	0.142
Capital investment	0.22	0.236	0.016	0.000***
Sale growth	0.387	0.177	−0.21	0.356
Lerner	0.089	−0.007	−0.096	0.012**
Inflation	2.392	2.397	0.005	0.787
Global financial crisis	0.246	0.248	0.002	0.762
Real GDP	9.649	9.648	−0.001	0.341

***, **, and * indicate mean difference-in-differences between treatment and control groups and are statistically significant at the 1%, 5% and 10% levels, respectively. The estimated difference-in-differences of 2.22% suggests that the intensive margin of R&D in the states significantly affected by the RPS program after 2015 increased compared to the non-adopting States without other covariates. However, when other covariates were included in the model, as shown in column 2 of Table 11, the interaction term “RPS Treated x Post period” shows a positive and statistically significant impact at 10%, suggesting that the Renewable Portfolio Standards (RPS) policy effectively increase the intensive margin of R&D for adopting States than non-adopting States.

Robustness tests

I conduct several robustness checks. I re-estimate the basic regressions (Table 13) using different measures of intensive margin of R&D by applying the Generalized method of moments (GMM). To account for the impact of lagged R&D investment on current investment (Bloom, 2007), I include two lags of the dependent variables into the model and use a dynamic panel generalized method of moments (GMM) estimator to address endogeneity concerns (Wintoki et al., 2012). In column 1, I measure intensive margins of R&D using R&D per total assets. The finding shows that the coefficient of climate change exposure is positive and statistically significant at 5%. Also, the coefficient of climate change is positive and statistically significant at 5% when R&D is divided employment. Climate change exposure influences R&D intensive margins positively and statistically significantly at 1% when average R&D is the measure for intensive margin of R&D. Overall, I reconfirm my findings using alternative dependent variables of the intensive margin of R&D.

Similarly, I use different measures for climate change exposure, including opportunities, regulation, and physical exposure. The estimated coefficients of the different measures of climate change exposure influence intensive margins of R&D positively and statistically significant at 1%. Compared with the baseline results, the effect of a one standard deviation increases in the climate change opportunity exposure increase intensive margin of R&D by 0.01%. Moreover, the economic interpretation of climate change regulatory exposure on intensive margin of R&D shows that one standard deviation increase in regulatory exposure leads to a 0.0068% increase in intensive margin of R&D. Furthermore, one standard deviation increase in climate change physical exposure leads to a 0.004% increase in intensive margin of R&D. The results remain consistent with the baseline findings that climate change exposure causes firms to increase their intensive margin of R&D, as shown in Table 14.

Table 11. Difference-in-difference after RPS Implementation.

	(1) R&D	(2) R&D
RPS Treated	0.0539***	0.0234***
	(0.0103)	(0.0083)
RPS Treated x Post period	0.0222**	0.0294*
	(0.0103)	(0.0161)
Post period	0.0136**	−0.0109
	(0.0057)	(0.0069)
climate change exposure		0.4974
		(0.4584)
Firm size		0.0036*
		(0.0019)
Cash holding		0.3224***
		(0.0717)
Profitability		−0.3873***
		(0.1485)
Tobin Q		0.0268
		(0.019)
Book to market ratio		−0.0012*
		(0.0006)
Capital investment		0.0074
		(0.0229)
Inflation		0.0046***
		(0.0012)
Federal interest rate		0.0021
		(0.0014)
Global Financial Crisis		0.0323***
		(0.0068)
Real GDP		−0.0061**
		(0.0027)
Observations	24923	24903
R-squared	0.0039	0.0669
Year Effects	Yes	Yes
Firm Effects	No	Yes
Industry Effects	No	No

Table 12. Interaction of post-period and treated effects and climate change exposure on the R&D intensive margin.

	(1) R&D	(2) R&D
climate change exposure	2.3189**	1.3615***
	(1.0724)	(0.3866)
Post period x CC exposure	2.1003*	
	(1.1087)	
Post period	0.0153	
	(0.0098)	
RPS treated		0.0154**
		(0.0073)
RPS treated x CC exposure		0.0141
		(0.9118)
Firm size	0.0037***	0.0037***
	(0.0012)	(0.0012)
Total debt	−0.027***	−0.0271***
	(0.0022)	(0.0022)
Firm age	−0.0006***	−0.0006***
	(0.0002)	(0.0001)
Cash holding	0.2567***	0.2559***
	(0.0484)	(0.0482)
Dividend dummy	−0.025***	−0.025***
	(0.003)	(0.003)
Profitability	0.1686***	0.1683***
	(0.0565)	(0.0565)
Tobin Q	0.0027	0.0027
	(0.0048)	(0.0048)
Book to market ratio	−0.00004	−0.0002
	(0.0005)	(0.0004)
Capital investment	−0.0132	−0.0136
	(0.0222)	(0.022)
Sale growth	0.0001	0.0001
	(0.0002)	(0.0002)
Lerner	−0.185***	−0.185***
	(0.0219)	(0.0219)
Constant	0.5128	−0.012
	(0.3562)	(0.1661)
Observations	24922	24922
R−squared	0.6652	0.6651
Year Effects	Yes	Yes
Firm Effects	Yes	Yes
Industry Effects	Yes	Yes
Controls	Yes	Yes

Table 13. Results of 2-way system GMM models.

VARIABLES	(1) RD/Assets	(2) RD/Emp	(3) Average R&D
$(\mathrm{RD/assets})_{t-1}$	0.4853***		
	(0.0038)		
$(\mathrm{RD/assets})_{t-2}$	−0.0161***		
	(0.0030)		
$(\mathrm{RD/Emp})_{t-1}$		0.5005***	
		(0.0005)	
$(\mathrm{RD/Emp})_{t-2}$		0.0656***	
		(0.0004)	
$(\mathrm{Avg\_RD})_{t-1}$			1.1504***
			(0.0001)
$(\mathrm{Avg\_RD})_{t-2}$			−0.0551***
			(0.0001)
Climate change exposure	0.0918**	7.3446**	7.1110***
	(0.0489)	(5.2854)	(33.1411)
Firm size	−0.0165***	4.8272***	2.8397***
	(0.0006)	(1.3749)	(0.3195)
Firm age	−0.0003***	−3.9659***	−1.4249***
	(0.0001)	(4.8554)	(0.0822)
Total debt	−0.0060***	−6.5721	−6.7488***
	(0.0023)	(2.9744)	(1.0881)
Cash holding	−0.0161***	6.8635***	−15.9940***
	(0.0019)	(0.2672)	(0.7556)
Dividend dummy	0.0021***	1.7150***	4.8482***
	(0.0005)	(1.5708)	(0.1713)
Profitability	−0.0518***	−8.6208***	−8.6894***
	(0.0026)	(3.1284)	(1.0516)
Tobin Q	−0.0001	−5.6941***	5.6620***
	(0.0002)	(6.7396)	(0.1554)
Book to market ratio	0.0006	−1.3002	−0.4221
	(0.0005)	(0.2328)	(0.9794)
Capital investment	0.0033**	8.5106**	−0.0460
	(0.0014)	(0.0380)	(0.7615)
Sale growth	0.0003***	3.2552***	−0.3494***
	(0.0000)	(1.7578)	(0.0447)
Market power	−0.0015***	−8.9753***	0.2501***
	(0.0001)	(4.0280)	(0.0739)
Constant	−0.2905***	−8.5299***	−6.4038***
	(0.0307)	(5.2267)	(1.1739)
Observations	20,205	19,779	20,204
Number of firms	2,018	1,998	2,018
Observation	20205	19779	20204
AR (1)	−4.476	−2.377	−2.219
AR (2)	0.334	0.154	0.547
Sargan	319.7	688.2	1015
Controls	Yes	Yes	Yes

Table 14. Different measures of climate change exposures on the intensive margin of R&D using GMM models.

VARIABLES	(1) Opportunity exposure	(2) Regulatory exposure	(3) Physical exposure
$(\text{RD/total asset})_{t-1}$	0.4670***	0.5421***	0.2135***
	(0.0043)	(0.0013)	(0.0115)
$(\text{RD/total asset})_{t-2}$	0.0077**	0.1398***	0.3556***
	(0.0031)	(0.0007)	(0.0110)
CC Opportunity exposure	0.007***		
	(0.0001)		
CC Regulatory exposure		0.023***	
		(0.0000)	
CC Physical exposure			0.028***
			(0.0004)
Firm size	−0.0130***	−0.0266***	0.0074***
	(0.0005)	(0.0000)	(0.0009)
Firm age	−0.0019***	−0.0027***	0.0013***
	(0.0002)	(0.0000)	(0.0003)
Total debt	−0.0121***	−0.0082***	−0.0166**
	(0.0028)	(0.0005)	(0.0067)
Cash holding	−0.0517***	−0.0552***	−0.0660***
	(0.0011)	(0.0002)	(0.0062)
Dividend dummy	0.0050***	0.0002	−0.0036
	(0.0010)	(0.0003)	(0.0023)
Profitability	−0.0690***	−0.0219***	−0.1274***
	(0.0018)	(0.0003)	(0.0074)
Tobin Q	0.0011***	−0.0032***	0.0060***
	(0.0001)	(0.0000)	(0.0002)
Book to market ratio	−0.0240**	2.0550***	0.0155
	(0.0105)	(0.3849)	(0.0803)
Capital investment	−0.0006*	−0.0137***	−0.0097***
	(0.0003)	(0.0001)	(0.0025)
Constant	0.0755	−1.3086***	−0.9648***
	(0.0485)	(0.0154)	(0.1051)
Observations	7,397	2,150	1,129
Number of firms	1,666	885	626
Observations	7397	2150	1129
AR (1)	−2.402	−1.392	−1.001
AR (2)	1.240	−1.661	0.830
Sargan	325.5	195.9	84.86
Controls	Yes	Yes	Yes

5. Conclusions

In this paper, I investigate the impact of climate change exposure on firms' intensive and extensive margins of corporate R&D investment. To capture firm-level climate change exposure, I use the dataset developed by Sautner et al. (2020), which measures exposure to opportunity, physical, and regulatory shocks caused by climate change. My analysis reveals that firms increase both their intensive and extensive margins of R&D in response to heightened climate change exposure. This effect is particularly pronounced for firms in carbon-intensive sectors, those with vertical integration, and those with greater growth opportunities.

I employ a difference-in-differences (DiD) approach to identify the causal effect, showing that firms in treated states implementing Renewable Portfolio Standards significantly increase their intensive margin of R&D. These findings are robust across alternative measures of climate change exposure and R&D intensity, providing a strong foundation for understanding how climate risks influence corporate innovation. The results highlight critical implications for climate policy and emphasize the need for firms to adapt their strategic management practices in response to climate risks.

My findings have several practical implications for corporate management and policymaking in the U.S. Understanding the link between climate change exposure and R&D investment for corporate management is crucial for aligning strategic goals with emerging environmental risks. Firms, particularly those in carbon-intensive sectors, should consider integrating climate risk assessments into their long-term R&D strategies to seize growth opportunities associated with climate adaptation and mitigation. This may involve investing in green technologies, developing climate-resilient products, or enhancing internal sustainability practices, ensuring companies are well-prepared for future regulatory changes and consumer preferences shifting towards eco-friendly solutions.

From a policymaking perspective, the study underscores the importance of promoting climate-related regulations that incentivize R&D investment in environmentally sustainable innovations. Policymakers can encourage firms to invest more in R&D by implementing stronger climate policies, such as Renewable Portfolio Standards or carbon pricing, that provide clear incentives for firms to focus on green technologies. Additionally, understanding how climate change impacts firms' R&D decisions can guide the design of support mechanisms for industries vulnerable to climate risks, ensuring that these firms remain competitive in a transitioning economy.

Use of AI tools declaration

I confirm that I did not use any artificial intelligence (AI) tools to generate or assist in writing this research paper. All content, analysis, and conclusions are entirely my own work.

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Conflict of interest

The author declares no conflicts of interest in this paper.

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