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The heat is on: An exploratory investigation of how climate change-related challenges affect SMEs' R&D activities

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DISCUSSION PAPER

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MAURICIO PEREZ-ALANIZ, AND CHRISTIAN RAMMER

The Heat Is On: An Exploratory Investigation of How Climate Change-Related Challenges Affect SMEs' R&D Activities

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The Heat is On: An Exploratory Investigation of How Climate Change-Related Challenges Affect SMEs' R&D Activities

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Abstract

Climate change can cause major challenges for Small and Medium-sized Enterprises (SMEs). Responding and adapting to such challenges is crucial, as SMEs are vital for driving economic growth and employment in most countries. Investing in R&D is a key way in which SMEs can build the capacities required for responding and adapting to climate change-related challenges. However, the extent to which such challenges affect SMEs' R&D activities remains a critical gap in existing knowledge. Using detailed firm-level data on 1,730 SMEs in Ireland, our study is the first to explore this issue. We achieve this, using information on SMEs' climate change-related challenges, from a new module of the 2018-2020 wave of the Irish part of the Community Innovation Survey (CIS), the Innovation in Irish Enterprises Survey (IIE). By combining a matching approach with probit regression analysis, we find that climate change-related challenges can increase the probability of SMEs investing in R&D. Such challenges can also increase the probability of SMEs engaging in continuous, as opposed to occasional R&D. Based on our findings, the above impacts are mainly driven by climate change, resulting in higher costs/input prices. Our study highlights the importance of R&D for SMEs to adapt and respond to climate change and provides critical insights for SMEs and policymakers alike.

Keywords: Climate change-related challenges, small and medium sized enterprises, research and development, climate change adaptation, climate change mitigation

JEL: Q54, Q55, O32, O33

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1. Introduction

Firms' economic and environmental activities are under the microscope, with pressure to mitigate and adapt to climate change-related challenges (European Commission 2022). In this context, Small and Medium-sized Enterprises (SMEs) can play a central role in the transition to net zero (European Commission 2023). Defined as firms with less than 250 employees (European Commission 2003), SMEs represent most firms in the global economy (Hampton et al. 2023). They are cumulatively responsible for approximately 63% of total CO_2 emissions in the business enterprise sector (European Commission 2022). Like most firms, SMEs are affected by climate change-related challenges in many ways. Extreme weather conditions for example, can drive up costs, damage infrastructure, and threaten business continuity (Bleda and Shackley 2008; Horbach and Rammer 2025). Climate change-related challenges can also affect the markets and regulatory environments in which SMEs operate. For example, changes in environmental policy can affect input and production costs (Lanoie et al. 2011). Encouraging SMEs to mitigate and adapt to climate change is vital for meeting existing climate goals, such as those outlined in the European Green Deal and the second Horizon Europe strategic plan 2025-2027 (European Commission 2019, 2024). Moreover, given the economic importance of SMEs, their failing to mitigate and adapt to climate change, also runs the risk of exacerbating irreversible damage to economies and societies more broadly (Hampton et al. 2023).

The objective of this paper is to provide an exploratory analysis regarding how climate change-related challenges incentivise SMEs to invest in R&D activities. We focus on R&D because, to effectively respond and adapt to climate change, SMEs may be required to adapt both their products and processes to meet consumer demand, while minimising the impact on the environment (Horbach and Rammer 2025). To achieve this, the development of cleaner production technologies (Marzucchi and Montresor 2017) and circular economy activities (Garrido-Prada et al. 2021) will be key. Therefore, investing in R&D can enhance SMEs' R&D capacities, which can be highly transformative for them, when responding and adapting to climate change-related challenges for two key reasons. Firstly, SMEs can become less dependent on external technology and develop new technologies that best fit their current and planned business activities. Secondly, improved R&D capacity can result in technological solutions that provide SMEs with a head-start *vis-à-vis* their competitors, including larger firms, when responding and adapting to the challenges imposed by climate change (Alam et al. 2022; Stern et al. 2022).

Despite the above, responding and adapting to climate change through increasing R&D efforts is not a straightforward task. SMEs typically have limited financial and human capital resources for R&D, which limits their abilities to respond and adapt to climate change-related challenges (De Blick et al. 2024). In addition, SMEs often face strong competition in the market while having limited market power (Brock and Evans 1989). This can affect SMEs' strategies to realign their products and services, when responding and adapting to climate change. Positive externalities, such as knowledge spillovers, may also prevent SMEs from investing in R&D, due to well-rehearsed non-appropriability arguments associated with R&D investments (Jaffe et al. 2002). In this sense, climate change-related challenges can result in two opposing effects on SMEs' R&D activities. On the one hand, such challenges can encourage SMEs to invest in R&D activities, despite the above-noted issues related to limited resources and imperfect/non-appropriability. On the other hand, climate change-related challenges can further exacerbate issues of limited resources for R&D, resulting in SMEs being unable to invest in R&D. However, to date, how climate change-related challenges affect SMEs' R&D activities remains a critical gap in existing knowledge (Albitar et al. 2023). As articulated by Unter et al. (2023 p. 3), "the literature on examining business responses to physical CC [climate change] conditions is still very limited". It is this knowledge gap that we seek to address in the current paper. Using information on the climate change-related challenges faced by SMEs in Ireland as our laboratory, the paper explores the following research question: *How do climate change-related challenges affect SMEs' R&D activities?*

By engaging in an exploratory investigation of the above research question, our study makes two key contributions to the existing literature. The first contribution is to provide a detailed understanding regarding how climate change-related challenges affect SMEs' R&D activities. An established body of literature focuses on the drivers of SME engagement in R&D (both within and outside of the firm), especially in the context of public R&D policy instruments (e.g. Hottenrott and Lopes-Bento 2014). Yet, this literature has to date, paid little attention to how specific climate change-related challenges affect SMEs' R&D activities. As Kesidou et al. (2023, p. 2) highlight, "given their significance in the business population and in terms of emissions, we know relatively little about what shapes SMEs' moves towards net zero". Another corpus of literature has focused on the development of eco-innovations (e.g. Triguero et al. 2013) and circular economy activities (e.g. Ghisetti and Montresor 2020) in SMEs. Only a very limited number of studies address the issue of how climate change affects SMEs' R&D activities. Where such studies do exist, they tend to focus on SMEs' innovation performance

(see, for example, Horbach and Rammer 2025). Insights from these studies suggest that climate change-related challenges have a positive effect on firm-level innovation performance. However, such studies do not examine the mechanisms through which climate change results in innovation performance effects. A focus on SMEs' R&D can provide this missing piece of the empirical puzzle, by identifying how climate change-related challenges affect SMEs' R&D activities. The ability to identify and understand the climate change-related challenges that underpin changes in SMEs' R&D activities is of strategic value to SMEs and policymakers alike. Such an understanding can help firms to strategically invest in opportunities that will enable and foster growth, while simultaneously protecting against climate challenges. It can also provide insights to policymakers regarding the design and implementation of targeted R&D support policy instruments, to help firms mitigate and adapt to climate change. To the best of our knowledge, ours is the first study to empirically investigate the effect of climate change-related challenges on SMEs' R&D activities.

Our second contribution is to provide a novel exploratory analysis of the firm-level R&D effects of climate change-related challenges. We achieve this by operationalising four new, to date unexplored variables included in the 2018-2020 wave of the Innovation in Irish Enterprises survey (IIE). These variables capture how firms experience the effects of climate change-related challenges on their business activities, including their R&D activities, by distinguishing four key climate change-related challenges: (1) Government policies or measures related to climate change; (2) Increasing customer demand for products that help mitigate or adapt to climate change; (3) Increasing costs or input prices resulting from climate change; and (4) Impacts of extreme weather conditions. Drawing on a recent study by Horbach and Rammer (2025), we operationalise these variables in two ways. Firstly, we construct a headline measure, indicating whether firms experience any of the above four climate change-related challenges. This is determined by whether the firm declared these factors to be of 'High or Medium importance' or 'Low importance' or 'Not relevant'. Secondly, we focus on how each specific climate change-related challenge affects SMEs' R&D activities. In our analysis we seek to mitigate issues of endogeneity (due to selection bias and reverse causality), using a Propensity Score Matching approach (Rosenbaum and Rubin 1983; Horbach and Rammer 2025). This is because some SMEs may be more likely to experience climate change-related challenges than others, based on characteristics such as, for example, their location and industrial sector. We then analyse the effect of climate change-related challenges on SMEs' R&D activities by means of probit regression analysis on the resulting matched sample.

The remainder of the paper is structured as follows. Section 2 discusses the conceptual framework and presents the hypotheses. Section 3 describes the data and empirical approach. Section 4 presents the results and discusses the findings. Finally, Section 5 discusses the potential implications for SMEs and policymakers, limitations of the study, and potential areas for future research.

2. Conceptual framework

SMEs are increasingly exposed to climate change-related challenges. These include: (1) Increased stringency of environmental policies and measures by governments (Riaz and Ali 2023); (2) Increased demand for more environmentally friendly products and services (Ghisetti and Montresor 2020); (3) Increased input costs related to climate change (European Central Bank 2022); and (4) Extreme weather conditions (Rising et al. 2022). These challenges affect all firms, but likely disproportionately impact SMEs given they typically have fewer resources and capabilities to deal with them, compared to their larger firm counterparts (Rising et al. 2022). SMEs also tend to be less able to shift their activities to other (less affected) locations, to adjust to changing climate conditions. In this context, investing in R&D is a key avenue through which SMEs can respond and adapt to these challenges and advance along a greener trajectory (European Commission 2018). This is especially true if SMEs focus their R&D activities on improving knowledge resources for environmental innovations (Horbach 2008) and improved environmental practices (Cuerva et al. 2014). It should also be borne in mind, however, that R&D focused on environmental issues is affected by a 'double externality' (Rennings 2000). This is because such R&D can generate both knowledge spillovers for other firms, and positive environmental externalities. Yet, firms may only be able to internalise a fraction of the returns from such R&D (Jaffe et al. 2005). Resultantly, SMEs in particular are dissuaded from investing in R&D, especially in R&D pertaining to environmental issues (Ortega-Argíles et al. 2009). In light of this, the section that follows focuses on how climate change-related challenges affect SMEs' R&D activities.

2.1 Climate Change-related challenges and SMEs' investing in R&D

We consider four climate change-related challenges as detailed above, and the mechanisms through which they are likely to affect SMEs' R&D activities. We begin by focusing on how extreme weather and higher input costs due to climate change, can affect whether SMEs invest in R&D. Extreme weather events can occur, for instance, in the form of flash floods, droughts,

and storms (Winn et al. 2011). Such events can result in damaged assets and infrastructure, delays to business operations, loss of raw materials and stock, and threats to the continuity of businesses (Halkos et al. 2018). This is especially true for those SMEs that are more susceptible to the variability of weather conditions. For instance, SMEs in directly weather-dependent sectors (e.g. agriculture) and with long-lived supply chains, such as distribution (Linnenluecke et al. 2012). The effects of increased input costs and physical damages resulting from climate change may be characterised as more context-dependent challenges. In other words, they can be determined by SMEs' firm-specific factors, including location, size, technological opportunities, and resource endowments (Lanoie et al. 2011). Besides SMEs facing extreme weather events themselves, similar effects can occur if extreme weather events affect the SMEs' key clients and suppliers (Halkos et al. 2018). R&D investment can be a key way SMEs respond and adapt to these extreme weather events and higher costs. Investing in R&D can enable SMEs to develop products and processes that are more resilient to extreme weather events (Horbach and Rammer 2025). Moreover, investment in R&D can strengthen SMEs' R&D capacity by reducing dependence on negatively affected resources, adapting their resource base, and improving the efficiency of existing resources (Pinkse and Gasbarro 2019).

SMEs may also face climate change-related challenges associated with regulatory and market demand changes. Climate change is shaping the regulatory environment and markets in which firms operate (European Commission 2022). As Lanoie et al. (2011) outline, regulations and policies are key enablers for SMEs to recognise potential cost savings associated with environment-oriented processes. Specifically, in the context of the EU, climate change adaptation and mitigation are key policy priorities, with firms considered as key actors in environmental policy implementation (European Commission 2019). Besides changes in the regulatory environment, changing consumer demand is another key way in which SMEs can be affected by climate change-related challenges (Horbach 2008). Consumers are increasingly aware of the roles firms play in achieving existing climate targets and goals. Therefore, they may prefer products and services from firms that engage in climate action. As a result, consumer preferences can influence firms' actions to align with environmental sustainability (Horbach et al. 2012). Investing in R&D can be a key avenue through which SMEs can respond to these changes in regulatory environments and consumer demand (Horbach et al. 2012). Such investment can support a proactive strategy against environmental risks, produce new knowledge and contribute to SMEs' absorptive capacity (Cohen and Levinthal 1990; Lee and Min 2015). Investing in R&D can thus drive a transformative change in SMEs, which tend to

face unique challenges compared to larger firms, in adopting and developing environmentally friendly innovations (del Río González 2009).

Having considered how four different climate change-related challenges can affect SMEs' R&D activities, our first hypothesis is as follows:

Hypothesis 1*: Climate change-related challenges will encourage SMEs to invest in R&D.*

2.2 Climate change and SMEs' engagement in continuous versus occasional R&D

Climate change-related challenges are a long-term and costly endeavour for SMEs (Alam et al. 2022). Therefore, this section discusses how for those SMEs that engage in R&D, climate change-related challenges can encourage them to engage in continuous (i.e. persistent R&D), as opposed to occasional (i.e. intermittent) R&D. In the limited literature where firms' engagement in persistent and intermittent R&D is studied, a variety of definitions of these concepts are employed (see for example, Mañez et al. 2015 and Ipinnaiye et al. 2025). For the purpose of this study, we define continuous R&D as SMEs engaging in R&D consistently over time, and occasional R&D as referring to firms engaging in R&D on an 'as needed' or *ad-hoc* basis.[1] We make this distinction because evidence emanating from the limited studies that do exist, suggests that continuous R&D aids firms in building their knowledge base through the learning associated with accumulating knowledge (Mañez and Love 2020). However, because of the high costs associated with R&D, sunk costs are a key mechanism to explain why some firms continuously invest in R&D, while others face entry barriers (Brancati 2023). This is because once firms invest in R&D, sunk costs may act as an incentive to continue to do so. At the same time, sunk costs can be an important barrier to continuous R&D in SMEs, because such firms often lack the required financial resources for continuous investment (Máñez and Vicente-Chirivella 2021). This is supported by an established literature which suggests that firm size influences firms' R&D strategies (Triguero and Córcoles 2013; Ipinnaiye et al. 2025).

[1] The definitions we employ in our study are in line with those used in earlier studies [e.g. Mañez et al. (2015), Mañez and Love (2020) and Ipinnaiye et al. (2025)]. As we detail later in Section 3.1, the definitions we use for continuous versus occasional R&D are also based on the IIE survey data questions available to us for this study and follow from discussions with Ireland's Central Statistics Office Statisticians. The statisticians highlighted that "The item is intended to measure whether enterprises are conducting R&D on a long-term basis or whether the projects are *ad hoc* ... the item does not specify whether continuous means throughout all three years or whether it could be a long-term project that started in 2020. Both of these should be classified as continuous because the intention of the item is to differentiate between *ad hoc* R&D performance and long-term planned projects".

Insights from this literature thus suggest that SMEs are more likely to engage in occasional R&D, when compared to their larger firm counterparts (Rammer et al. 2009).

Despite the above, we suggest that climate change-related challenges will encourage SMEs to engage in continuous, as opposed to occasional R&D. Underpinning this reasoning is the fact that, as discussed in Section 2.1, climate change-related challenges can have important impacts internally (e.g. costs and risks) and externally to the firm (e.g. regulatory and market conditions). Moreover, the full impacts of climate change remain highly unknown. Yet, it is now well established, that responding and adapting to climate change requires deep firm-level changes, including developing and implementing business models that align with sustainability objectives (Sarpong et al. 2023). Engaging in R&D is vital for SMEs transitioning to such sustainable business models, and achieving this is unlikely to take place quickly. Doing so requires continuous efforts by SMEs to develop and accumulate new knowledge (Mañez and Love 2020; Ipinnaiye et al. 2025). Failing to do so, can result in SMEs being unable to adapt to the new business conditions that climate change presents. Therefore, and despite the market failures noted earlier, we hypothesise that SMEs experiencing climate change-related challenges will be more likely to engage in continuous as opposed to occasional R&D efforts. Our second hypothesis is thus as follows:

Hypothesis 2: *Climate change-related challenges will increase SMEs' engagement in continuous, as opposed to occasional R&D.*

3. Data and Empirical Approach

3.1. Data

Our paper provides an in-depth exploratory analysis of the effects that climate change-related challenges have on SMEs' R&D activities. We achieve this by using firm-level data from the Innovation in Irish Enterprises survey (IIE, formerly the Irish contribution of the Community Innovation Survey [CIS]). This is a biannual survey carried out by the Irish Central Statistics Office (CSO), following the guidelines of the Oslo Manual (OECD and Eurostat 2018). The survey comprises a representative sample of enterprises based in Ireland from industry and selected services, with 10 or more employees.[2] The IIE survey provides detailed information

[2] The IIE includes enterprises from the following NACE Rev. 2 Sector Classification: 05-39, 46, 49-53, 58-66, 71-73 with 10 or more persons employed. It has a sample frame of approximately 4,450 enterprises, with an

on firms' R&D and innovation activities, and key firm-level characteristics. Importantly, the 2018-2020 IIE survey wave included a new module, pertaining to the climate change-related challenges that firms faced during the period 2018 to 2020. In a similar vein to Horbach and Rammer (2025), our analysis is based on the questions included in this module. The top panel of Table A1 in the Supplementary Material accompanying this paper provides a detailed description of these specific questions. Our exploratory analysis primarily uses the 2018-2020 IIE survey wave, which includes a total of 2,190 firms. We also use data for the firms during the previous two IIE survey waves (i.e. 2014-2016 and 2016-2018). As we outline later in Section 3.3, these data enable us to mitigate potential issues of endogeneity affecting the probability of SMEs to experience climate change-related challenges. Given that our analysis specifically focuses on SMEs, we exclude large-sized firms from our working sample (i.e. firms with 250 or more employees). This results in a working sample of 1,730 SMEs. Of these, 849 SMEs experienced climate change-related challenges during 2018-2020, while 881 SMEs did not experience such challenges.

3.2 Key variables of interest

Our exploratory analysis focuses on two key measures of firm-level R&D. To test our first hypothesis, regarding climate change-related challenges encouraging SMEs to invest in R&D, we use a binary variable which equals 1 if the SME invests in R&D, otherwise, the value is 0 (Del Rio et al. 2024). Our second measure of R&D comprises a binary variable which equals 1 if the firm engages in R&D on a continuous basis during the period 2018 to 2020, otherwise, the value is 0. We use this measure of R&D when testing our second hypothesis. The bottom panel of Table A1 in the Supplementary Material accompanying this paper presents the specific IIE survey questions used to construct both firm-level R&D variables.

Our key independent variables of interest pertain to climate change-related challenges. We obtain this information directly from the 2018-2020 IIE survey wave. The top panel of Table A1 in the Supplementary Material accompanying this paper provides the questions firms are asked regarding climate change-related challenges. These challenges include: (1) Government policies or measures related to climate change; (2) Increasing customer demand for products that help mitigate or adapt to climate change; (3) Increasing costs or input prices resulting from

average response rate of 51 percent (CSO 2022). For further details see: https://www.cso.ie/en/methods/technologyandinnovation/innovationinirishenterprisesformerlyknownascommunityinnovationsurvey/.

climate change; and (4) Impacts of extreme weather conditions. In responding to these questions, firms were required to select one option from the following four-item scale: (1) High Importance; (2) Medium Importance; (3) Low Importance; or (4) Not Relevant.

Based on the above, we construct five key variables of interest. The first variable is a headline measure, which equals 1 if firms experienced any of the above-noted climate change-related challenges at 'medium' or 'high' levels of importance. This approach is in line with studies focused on firms' obstacles to innovation using CIS survey data (e.g. Perez-Alaniz et al. 2024). The remaining four variables pertain to each of the four challenges, in binary form. We follow Horbach and Rammer (2025) and create variables that equal 1 if a firm indicates the challenge to be of "high" or "medium" importance to their business. Otherwise, the value is 0. Table 1 summarises our dependent and key independent variables for the whole sample (Column 1), and for SMEs that experienced (Column 2) and did not experience (Column 3) climate change-related challenges.

Table 1: Summary statistics of the outcome and key explanatory variables

	Total sample				**Climate change-related challenges (1=Yes)**				**Climate change-related challenges (0=No)**			
Dependent Variables	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Invest in R&D (1 = Yes)	0.316	0.465	0	1	0.361	0.480	0	1	0.274	0.446	0	1
Continuous R&D (1 = Yes)	0.637	0.481	0	1	0.639	0.481	0	1	0.636	0.482	0	1
Independent variables												
Climate change-related challenges	0.490	0.500	0	1	1	0	1	1	0	0	0	0
Government policies/ measures	0.307	0.461	0	1	0.626	0.483	0	1	0	0	0	0
Consumer demand	0.281	0.449	0	1	0.573	0.494	0	1	0	0	0	0
Extreme weather conditions	0.219	0.413	0	1	0.446	0.497	0	1	0	0	0	0
Higher input costs or prices	0.345	0.475	0	1	0.703	0.457	0	1	0	0	0	0

Note: The variable Invest in R&D (1 = Yes) considers all SMEs in the sample. The variable Continuous R&D (1 = Yes) only considers SMEs that invested in R&D (i.e. Invest in R&D = 1).

As Table 1 shows, 49 percent of SMEs experienced such challenges, based on our headline measure. Of these, 62.6 percent of SMEs experienced challenges related to government policies or measures related to climate change, while 57.3 percent of SMEs faced challenges associated with increased customer demand for products that help mitigate or adapt to climate change. We also observe that 70.3 percent of the SMEs that experienced climate change-related challenges, faced challenges related to increasing costs or input prices resulting from climate change. Finally, 44.6 percent of such SMEs faced challenges related to extreme weather conditions. Additionally, we consider that SMEs may have experienced all four climate change-related challenges. Table B1 in the Supplementary Material accompanying this paper presents a

correlation matrix, which shows that all the correlation coefficients between these variables are below 0.7. This indicates that there is sufficient variability between these variables for our analysis.

3.3. Empirical approach

In analysing whether (and how) climate change-related challenges affect SMEs' R&D activities, we need to consider potential issues of endogeneity due to self-selection and reverse causality (Ayoub and Lhuillery 2024). This arises because firms from different sectors and of different sizes, may vary in their propensity to be impacted by climate change-related challenges. For example, SMEs in sectors such as agriculture, energy and water, can be more vulnerable when it comes to being affected by climate change-related challenges (Linnenluecke et al. 2012). Likewise, smaller SMEs may have fewer resources to address issues including those of climate change, in comparison to larger-sized SMEs (Perez-Alaniz et al. 2023). SMEs with lower levels of technological capabilities may also find it more difficult to respond to climate change-related challenges, in comparison to highly technologically capable SMEs (Bataineh et al. 2024). Besides selection bias, we also need to consider potential issues of reverse causality between SMEs' R&D activities and the extent to which they experience climate change-related challenges. This is because past R&D efforts may alter the way and extent to which climate change is relevant to SMEs. A key reason for this is that SMEs that invest in R&D, tend to typically operate in international markets (Esteve-Pérez and Rodríguez 2013), thus exposing them to climate change-related challenges, most notably regarding changes in regulatory environments (Alam et al. 2022). Failing to consider these issues can bias our results.

To address the above issues of endogeneity, we employ a two-stage modelling approach. In the first stage, we control for the probability of SMEs to experience climate change-related challenges, with a propensity score matching (PSM) approach. PSM is typically used in the context of impact-effect evaluations. Examples include evaluations regarding the impact of firm-level public R&D supports on firm-level R&D and innovation (Czarnitzki and Delanote 2015; Lenihan et al. 2024b). In such contexts, the PSM approach relies on the conditional independence assumption (CIA), where treatment and outcome are assumed to be statistically independent for firms with the same set of observable characteristics (Rubin 1977).

Outside of the above contexts, studies such as Klingebiel and Rammer (2021), Lenihan et al. (2024c), and Horbach and Rammer (2025), show that PSM can also be used as a sample-balancing tool. Our approach is in line with these studies. For example, Horbach and Rammer (2025) use PSM when analysing the impact of the same climate change-related challenges used in our study, on firms' innovation activities. In their specific case, the authors employ PSM to match firms that are affected by climate change, with statistically similar firms that are not affected by climate change. We follow the same approach in the current paper.

In our case, we use PSM to construct a working sample comprising: (1) SMEs that experienced climate change-related challenges during 2018 to 2020; and (2) SMEs that were statistically identical to firms that experienced climate change-related challenges up to 2018, but that did not experience such challenges during 2018 to 2020. In doing so, we ensure that matched SMEs have the same levels of R&D investments, before they declare experiencing climate change-related challenges. In this context, we assume that any observed difference between these two groups of SMEs, in terms of their R&D activities, originates in response to climate change-related challenges. We implement our PSM approach by estimating SMEs' probabilities of being affected by climate change-related challenges using the following logit model:

$$Pr(ClimateChange_{dit}) = \alpha + \beta_1 X'_{\text{it-1}} + \varepsilon_i \qquad (1)$$

Where $ClimateChange_{dit}$ is a dummy variable, and *Pr* refers to the probability of firm *i* being affected by a climate change-related challenge of type *d* in period *t* (i.e. 2018-2020). X' is a vector of covariates for firm *i* that are assumed to influence the probability of a firm being affected by climate change-related challenges, in period *t-1* (i.e. 2016-2018). We discuss the variables included in X' in Section 3.4 below. The terms α and ε refer to the intercept and error terms, respectively, while β_1 is our coefficient of interest. We present the results of the logit estimation in Table C1 in the Supplementary Material accompanying this paper, as average marginal effects. From Equation (1), we obtain the propensity scores, which are SMEs' probabilities of experiencing climate change-related challenges. Following this, we match SMEs based on their propensity scores, by following a three nearest neighbours matching routine (Lenihan et al. 2024c).[3] In doing so, we use a caliper of 0.2 points of the standard deviation (Austin 2011).

[3] Using the 1:3 nearest neighbour matching approach as opposed to 1:1 matching has a trade-off between variance and bias. In other words, by using more information to construct the counterfactual for each firm, we achieve reduced variance, but increased bias as a result of poorer matches (Smith 1997).

The second step of our analysis comprises running a regression analysis using our matched sample. We achieve this by estimating Equation (2) as follows:

$$RD_{\text{dit}} = \alpha + \beta_1 ClimateChange_{dit} + \beta x X'_{\text{dit-1}} + \varepsilon_{\text{i}} \quad (2)$$

RD refers to the R&D activity $_d$ of firm i in period t (t = 2018-2020). $ClimateChange_{dit}$ and X' represent the same variables as used in the matching approach (see Equation 1). Including these control variables in our analysis ensures that our approach controls for any remaining differences in the observable characteristics used for matching with PSM. Similar to Equation (1), α and ε refer to the constant and robust standard error term, respectively. Finally, β_1 is our main coefficient of interest. In testing our hypotheses, we estimate Equation (2) using two separate probit regression models. Moreover, as discussed in Section 3.2, our analysis considers a headline measure of climate change-related challenges, and considers each of the four challenges individually. This means that we estimate Equation (2) using a probit regression model a total of four times (given that we use two dependent variables pertaining to the two hypotheses, and for two different sets of independent variables). Importantly, while we use the entire sample of firms when testing Hypotheses 1, our analysis of Hypothesis 2 is carried out by only focusing on SMEs that invest in R&D. This is because, only those firms that invest in R&D, are required to declare whether such R&D was carried out on a continuous or occasional basis, in the 2018-2020 IIE survey wave. As presented in Section 4.2, the results obtained with the above approach are robust to different matching and model specifications.

3.4 Matching and control variables

As discussed in Section 3.2, our empirical analysis uses a set of detailed matching and control variables to model the probability of SMEs experiencing climate change-related challenges, and how such challenges impact their R&D activities. As Table 2 below shows, we include a set of variables which account for SMEs' key characteristics. In the context of firms in Ireland, Perez-Alaniz et al. (2023) note that small-sized firms may be very different than medium-sized firms, in terms of their abilities to engage in R&D. To control for this, we include a dummy which equals 1 for firms with fewer than 50 employees (i.e. small-sized firms) and 0 otherwise (European Commission 2003).[4] Firms that belong to an enterprise group may also be very

[4] As a robustness check, we check for the possible differential effect that climate change-related challenges may have on small and medium-sized firms' R&D activities. We discuss this robustness check in further detail in Section 4.2.

different, in terms of levels of capabilities and resources, in comparison to individual stand-alone firms (Ayoub and Lhuillery 2024). The same applies for subsidiary (foreign-owned) firms of international corporations, *vis-à-vis* Irish-owned firms (Lenihan et al. 2024b). We control for these characteristics using dummy variables.[5] Finally, we include sector dummy variables, using two-digit NACE Rev. 2 Sector Classification (see Table D1 in the Supplementary Material accompanying this paper).

It should also be noted that SMEs' performance in the market and their past R&D and innovation activities can play a key role in terms of: (1) The likelihood of SMEs experiencing climate change-related challenges; and (2) The responses SMEs may adopt when faced with such challenges. We consider these issues in our empirical approach by including: (1) A continuous variable for the natural logarithm of a firm's average turnover per employee during the period 2016 to 2018 (Perez-Alaniz et al. 2024); and (2) a binary variable measuring a firm's sales obtained from exports from 2016 to 2018 (Love and Roper 2015). Regarding R&D and innovation activities, our empirical approach considers firms' total R&D and innovation expenditure in 2018 (i.e. the base year).

Beyond the above, engaging in R&D collaborations with external partners is a key way in which SMEs can source external knowledge for R&D and innovation (Hervás-Oliver et al. 2021). Following Roper et al. (2008), we include binary variables to measure the following four key external knowledge sources that firms may engage with: (1) Forward linkages (i.e. Customers or clients); (2) Backward linkages (i.e. Suppliers or external consultants or private research institutes); (3) Horizontal linkages (i.e. Competitors) and (4) Public knowledge linkages (i.e. Universities or public research centres).[6] Finally, we include other factors (within and outside of the firm) which can affect the extent to which SMEs engage in R&D. For example, firms may refrain from engaging in R&D if they face financial and/or knowledge constraints (Hall et al. 2016; Filippopoulos and Fotopoulos 2022). We therefore include two dummy variables to control for these issues. It should also be noted that the receipt of public financial support for R&D, such as R&D tax credits, can encourage SMEs to engage more in R&D and innovation activities (Lenihan et al. 2024a). We account for this with a variable measuring whether firms claimed R&D tax credit funding.

[5] As outlined by Lenihan et al. (2024b), this is a particularly important issue in the case of Ireland, given the reliance of the economy on foreign-owned multinational enterprises.
[6] See Roper et al. (2008) for a more detailed discussion of these distinct knowledge-sourcing activities.

Table 2: Description of matching variables

Matching variables (2016-2018)	Description
Enterprise group	Binary variable =1 if a firm is part of an enterprise group, otherwise = 0.
Domestic	Binary variable =1 if a firm is Irish-owned, otherwise = 0.
Average turnover (logarithm)	Natural logarithm of a firm's turnover per employee (average of 2016-2018).
Exports	Binary variable =1 if 50% or more of a firm's turnover is from exports to markets outside of Ireland, otherwise = 0.
Invest in R&D	Binary variable =1 if a firm invested in R&D, otherwise = 0.
Continuous R&D	Binary variable =1 if a firm engaged in continuous R&D, otherwise = 0.
Total R&D and innovation expenditure (logarithm)	Natural logarithm of a firm's total R&D and innovation expenditure (incl. R&D).
Forward linkages	Binary variable =1 if a firm cooperated with customers/clients, otherwise = 0.
Backward linkages	Binary variable =1 if a firm cooperated with suppliers, external consultants or private research institutes, otherwise = 0.
Horizontal linkages	Binary variable =1 if a firm cooperated with competitors, otherwise = 0.
Public knowledge linkages	Binary variable =1 if a firm cooperated with universities, higher education institutions or public research institutes, otherwise = 0.
Financial obstacles	Binary variable =1 if a firm faced financial obstacles to R&I, otherwise = 0.
Knowledge obstacles	Binary variable =1 if a firm faced knowledge obstacles to R&I, otherwise = 0.
R&D tax credit	Binary variable = 1 if a firm claimed an R&D tax credit (i.e. in 2018-2020), otherwise = 0.
Firm size	Binary variable =1 if a firm is small (fewer than 50 employees), otherwise = 0.
Firm sector	Binary variables representing 9 NACE Rev. 2 Classification Sections

Note: All of the above matching variables are measured at the base year by using data from the 2016-2018 IIE survey wave. The only control variable which is measured during the 2018-2020 period is whether firms claimed R&D tax credits (due to no available data on this variable in 2016-2018). In a small number of cases, obtaining data for the Innovation in Irish Enterprises (IIE) 2016-2018 survey wave was not possible due to missing data. In such cases, we use the previous IIE survey wave data (i.e. in 2014-2016) so as to maximise the number of observations in the analysis.

3.5 Descriptive statistics

Table 3 presents the descriptive statistics for all variables used in the analysis, when considering: (1) All SMEs in the sample; (2) SMEs that experienced climate-change related challenges; and (3) SMEs that did not experience climate-change related challenges. As discussed earlier in Section 3.2, approximately half of the SMEs in the sample experienced climate change-related challenges.

Table 3. Descriptive statistics for the matching variables

	Total sample				Climate change-related challenges (1=Yes)				Climate change-related challenges (0=No)			
Matching Variables (i.e. in 2016-2018)	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Enterprise group	0.307	0.461	0	1	0.313	0.464	0	1	0.300	0.458	0	1
Domestic	0.834	0.371	0	1	0.829	0.376	0	1	0.839	0.366	0	1
Average turnover (logarithm)	5.255	2.186	0	15.413	5.303	2.238	0	15.413	5.208	2.134	0	13.121
Exports	0.676	0.468	0	1	0.669	0.479	0	1	0.683	0.465	0	1
Invest in R&D	0.285	0.451	0	1	0.275	0.446	0	1	0.294	0.456	0	1
Continuous R&D	0.624	0.484	0	1	0.632	0.482	0	1	0.616	0.486	0	1
Total innovation expenditure (log.)	2.343	2.864	0	12.901	2.282	2.851	0	11.648	2.401	2.877	0	12.901
Forward linkages	0.173	0.378	0	1	0.181	0.385	0	1	0.165	0.372	0	1
Backward linkages	0.224	0.417	0	1	0.226	0.418	0	1	0.223	0.416	0	1
Horizontal linkages	0.109	0.312	0	1	0.108	0.311	0	1	0.110	0.313	0	1
Public knowledge linkages	0.152	0.359	0	1	0.157	0.364	0	1	0.147	0.354	0	1
Financial obstacles	0.502	0.500	0	1	0.519	0.499	0	1	0.485	0.500	0	1
Knowledge obstacles	0.443	0.496	0	1	0.454	0.498	0	1	0.433	0.495	0	1
R&D tax credit	0.110	0.314	0	1	0.107	0.309	0	1	0.114	0.318	0	1
Firm size (<50 employees)	0.610	0.487	0	1	0.601	0.489	0	1	0.618	0.486	0	1

Note: All the matching variables above are measured using the 2016-2018 IIE survey wave. The only control variable which is measured during the 2018-2020 period is whether firms claimed R&D tax credits. In a small number of cases, obtaining data for the IIE 2016-2018 survey wave was not possible due to missing data. In such cases, we use the previous IIE survey wave data (i.e. in 2014-2016) so as to maximise the number of observations in the analysis.

As Table 3 shows, SMEs that experienced and did not experience such challenges are somewhat similar, when we consider the variables presented in the table. Despite this, there are some important differences. One key difference is that a greater proportion of SMEs affected by climate change-related challenges reported facing financial and knowledge constraints (51.9 and 45.4 percent respectively). Moreover, a smaller proportion of SMEs that experienced climate change-related challenges claimed R&D tax credits (10.7 percent), compared to those firms that did not experience climate change-related challenges (11.4 percent). Finally, SMEs that experienced climate change-related challenges exhibited lower levels of R&D investments, when compared to firms that did not experience such challenges (27.5 and 29.4 percent respectively).

The above differences support our decision to use PSM as a sample balancing tool. Tables E1 and E2 in the Supplementary Material accompanying this paper present the balance checks, resulting from these two matching processes. As these tables show, no significant differences remain between firms that experienced climate change-related challenges, and firms that did not experience such challenges. This is the case across all the observable characteristics considered in the matching process. This suggests that our matching processes have been effective at balancing the sample. We can now proceed to present and discuss our main findings.

4. Results and discussion

4.1. Main results

Our main findings are presented in Table 4. We begin by focusing on our headline measure of climate change-related challenges. The results obtained with this measure are presented in Columns 1 and 3. In Column 1, we observe that for SMEs that experienced climate change-related challenges, the probability to invest in R&D is approximately 32.3 percentage points higher ($p < 0.01$). This is in comparison to SMEs that did not experience climate change-related challenges. Column 3 indicates that climate change-related challenges do not affect the probability of SMEs engaging in continuous R&D, as opposed to occasional R&D (i.e. the result is not statistically significant).

We now turn to the individual effects of the four climate change-related challenges, where a more nuanced picture unfolds. The individual effects are reported in Columns 2 and 4 of Table 4. In Column 2, we observe that the above noted effects on SMEs' probabilities to invest in

R&D, are mainly driven by climate change-related challenges related to consumer demand and higher costs ($p < 0.01$ and $p < 0.05$, respectively). In Column 2, we also observe that climate change-related challenges associated with extreme weather conditions have a negative effect on the probability of SMEs investing in R&D ($p < 0.1$). Finally, we find that challenges related to regulation/policy measures, have no effect on the probability of SMEs investing in R&D. Focusing now on Column 4, we find only those climate change-related challenges pertaining to increasing input costs to affect the probability of SMEs engaging in continuous as opposed to occasional R&D ($p < 0.05$). We also find, in a similar vein to Columns 1 and 3, that climate change-related challenges associated with physical damage, have a negative effect on the probability of SMEs engaging in R&D on a continuous basis ($p <0.05$).

Table 4. Main results

Dependent variables	**(1)** Invest in R&D (Binary Variable)	**(2)** Invest in R&D (Binary Variable)	**(3)** Continuous R&D (Binary Variable)	**(4)** Continuous R&D (Binary Variable)
Climate change-related challenges	0.323***		0.125	
	(0.073)		(0.136)	
Regulations/Policy measures		0.153		-0.016
		(0.104)		(0.091)
Consumer demand		0.299***		0.088
		(0.104)		(0.164)
Extreme weather conditions		-0.180*		-0.217**
		(0.099)		(0.093)
Higher costs/Input prices		0.203**		0.187**
		(0.094)		(0.086)
Controls	Yes	Yes	Yes	Yes
Observations	1,619	1,619	480	480

Note: *** $p < 0.01$, ** $p < 0.05$, * $p <0.1$. Robust standard errors in parentheses. The main results presented in Column 1 and Column 3 are obtained using a probit regression model on the binary outcome variables. Columns 2 and 4 report the results of the effect of each climate change-related challenge on R&D activities, using a probit regression model. Controls are included but not reported. The coefficients in Columns 1 and 2 are obtained using the whole sample, while the coefficients in Columns 3 and 4 are based on SMEs that invested in R&D. This explains the differences in the number of observations between these columns.

Our combined findings indicate that relying on a single overarching measure of climate change-related challenges may fail to accurately reflect the specific factors driving the observed changes in SMEs' R&D activities. In this context, our analysis provides some support for our hypotheses, but highlights a number of caveats. For example, in the case of Hypothesis 1, we suggested that climate change-related challenges will encourage SMEs to invest in R&D. Our findings indicate that SMEs that experience climate change-related challenges related to higher

input prices or costs and consumer demand, do have a greater probability to invest in R&D. In line with Horbach (2008), it is possible that investing in R&D enables SMEs to produce and modify innovations and production methods that respond to and align with, changing consumer pressures. This is also in line with studies that highlight the importance of market factors, such as consumer demand, for encouraging firms to develop environmental innovations (e.g. Horbach et al. 2012). Moreover, as noted earlier, increasing costs due to climate change-related challenges may prompt SMEs to seek new ways of carrying out business activities, resulting in them being more likely to invest in R&D.

Despite the above, we find climate change-related challenges associated with extreme weather decrease the probability of SMEs to invest in R&D. As Linnenluecke et al. (2012) outline, extreme weather events are uncertain and increasing in severity, causing destruction to firm-level operations. Additionally, as outlined by Lei and Xu (2024) in the context of firms in China, extreme weather events (particularly typhoons), have a negative effect on firms' R&D and innovation activities. This is partly because of substantial infrastructure damage and loss from extreme weather. Based on this, it is possible that SMEs that are physically impacted by climate change and face similar losses, may be ill-prepared to respond to such extreme weather events through the allocation of resources to R&D. Finally, our results suggest that climate change-related challenges associated with government policies/measures have no effect on the probability of SMEs investing in R&D. This is somewhat surprising, given that environmental regulations have been highlighted as a driver of eco-innovations and cleaner technologies in several studies (e.g. Khanna et al. 2009). One possible reason why our results differ may be because such regulatory effects can differ across environmental technology fields (Frondel et al. 2008). Environmental regulation has been established as a key driver of end of pipe technologies, which generally do not require firms to engage in R&D (Garcia-Quevedo et al. 2022). Moreover, R&D intensive activities, such as the development of cleaner technologies, may be mainly driven by possible cost savings (Frondel et al. 2008). However, given our data, we cannot fully ascertain that this is indeed the case.

Turning our focus to Hypothesis 2, we proposed that climate change-related challenges will drive firms to engage in continuous (as opposed to occasional) R&D. In this context, when using our headline measure for climate change-related challenges, we do not find any statistically significant effect on SMEs' engagement in continuous R&D. However, our results provide a different picture when we analyse each of the four climate change-related challenges individually. More specifically, our results support Hypothesis 2 in the context of climate

change-related challenges associated with higher costs and input prices, encouraging engagement in continuous R&D. As discussed in Section 2, climate change can have important cost implications for SMEs (Winn et al. 2011). The existing literature suggests that SMEs are burdened by the sunk costs of long-term R&D investments that act as a barrier to continuous R&D engagement (Máñez and Love 2020). However, given the deep-rooted changes required by climate change, SMEs may find that 'one off' R&D investments are not suitable in the long term. Indeed, Ipinnaiye et al. (2025) note that continuous R&D can drive innovation success among smaller firms more reliably than occasional R&D efforts. As a result, instead, the nature of climate change-related challenges may demand the transformation of business activities over time (Alam et al. 2022), thus encouraging continuous investment in R&D by SMEs. Interestingly, by contrast, we find that extreme weather conditions result in SMEs being less likely to engage in continuous R&D. As noted earlier, physical impacts from climate change may result in human and financial loss and damage to infrastructure (Lei and Xu 2024). Lee et al. (2025) find (in the case of Chinese A listed firms) that risks from extreme weather events can result in firms addressing immediate challenges, including potential losses through, for example, repairing and rebuilding. This can come at the expense of allocating resources to long-term R&D investment focused on resilience. Therefore, it is possible that SMEs' abilities to invest in more continuous R&D, may be constrained because of engaging in short-term environmental actions (He et al. 2024).

4.2 Additional analysis and robustness tests

To test the robustness of our findings, we use an alternative matching approach, in the form of entropy balancing (Hainmueller 2012). As some studies have suggested, matching firms based on propensity scores does not fully account for the firm-level characteristics as contained in the matching covariates (Guy et al. 2021). Moreover, PSM tends to discard observations which do not satisfy the zone of common support (Hainmueller 2012). Entropy balancing overcomes these issues. This is because entropy balancing is an alternative weighting method on the sample observations that adjusts the pre-existing weights to meet the balance conditions. By specifying probability weights, entropy balancing produces final weights that remain close to the original probability weights, and achieve covariate balance across the specified covariate moments. In this regard, entropy balancing retains efficiency, without discarding any observations from the sample (Hainmueller 2012). By including covariate balance in the main estimation process, entropy balancing adds an additional layer of robustness to our estimates. A central reason for

this is that entropy balancing will yield consistent estimates even if our impact model (probit) is mis-specified (Zhao and Percival 2017). Entropy balancing is thus wholly appropriate to test the robustness of our main findings.

Table F1 in the Supplementary Material accompanying this paper, presents the results obtained from applying the entropy balancing approach. Specifically, we observe that the coefficient for climate change-related challenges affects the probability of investing in R&D. This is also the case for the coefficient capturing the effect of climate change-related challenges on SMEs' engagement in continuous R&D (both are fully in line with our main approach). Turning to the effects of each climate challenge, the coefficient capturing the effect of higher input costs on SMEs' investment in R&D and continuous R&D remains positive and statistically significant. At the same time, the effect of extreme weather conditions remains negative and statistically significant. Given the above, the results obtained using this additional analysis largely support our main findings in Table 4.

In addition to the above, and as discussed in Section 2, firm size can have an important effect with regards to R&D activities (Perez-Alaniz et al. 2023). Therefore, we test the effect of climate change-related challenges on SMEs' R&D activities in small-sized and medium-sized firms, separately. Table G1 in the Supplementary Material accompanying this paper presents the results of this additional analysis. The coefficients in Columns 1 and 2 are obtained by estimating Equation (2) with a Probit regression model, and a new variable capturing the interaction between climate change-related challenges and small-sized firms.[7] Our findings suggest that climate change-related challenges have similar effects on the R&D activities of all SMEs, regardless of whether they are small or medium-sized. In all instances, the findings concur with our main findings as presented in Table 4. Therefore, we conclude that the robustness tests support the findings of our main approach.

5. Conclusion

Investing in R&D is a key way for firms, especially SMEs, to respond and adapt to climate change-related challenges. However, the extent to which such climate change-related challenges affect SMEs' R&D activities remains unexplored (Albitar et al. 2023). Our paper

[7] As there are no marginal effects for interaction terms in non-linear models, we instead use the discrete difference in predicted probabilities between both groups of firms (i.e. small firms experiencing climate change-related challenges and medium-sized firms experiencing climate change-related challenges) (Greene 2010). As a result, we examine the effect of climate change-related challenges at different values of firm size.

addresses this key gap in existing knowledge, by using data from a novel module of the Innovation in Irish Enterprises Survey, comprising information on the climate change-related challenges affecting firms. To the best of our knowledge, our study is the first to provide a detailed exploratory analysis of whether (and how) climate change-related challenges affect SMEs' R&D activities.

Our analysis enables us to identify channels through which climate change-related challenges affect the probability of SMEs investing in R&D and the probability of SMEs engaging in R&D continuously. We find that the effects of the four climate change-related challenges on SMEs' R&D activities are highly heterogenous. Our findings mainly indicate that cost pressures related to climate change and changing consumer demand, encourage SMEs to invest in R&D, and increase the probability of SMEs engaging in continuous R&D. This may suggest that SMEs identify early and continuous investments in R&D, as a key mechanism to gain a competitive edge in the context of climate change altering their business environment. Such sustained investments in R&D know-how can translate to the production of environmentally friendly products and their enabling technologies. In turn, this can result in benefits, including cost-saving opportunities (Alam et al. 2019). We also find that physical damages from climate change reduce the probability of SMEs investing in R&D, and decrease their engagement in continuous R&D. This may be explained by the unpredictability of extreme weather and the immediate impacts that are likely to follow (Pinkse and Gasbarro 2019).

Given the existing gaps in the literature surrounding climate change-related challenges and SMEs' R&D activities, this paper makes two key contributions. Our first contribution enhances our understanding regarding how climate change-related challenges affect SMEs' R&D activities. To date, studies have mainly focused on the issue of climate change and innovation (e.g. Horbach et al. 2012; Horbach and Rammer 2025), or climate issues in the context of large-sized firms (Gasbarro et al. 2017). This leaves an important gap in our understanding of how climate change affects SMEs, which represent most firms in the global economy. Our study represents an important step in addressing this knowledge gap. This is paramount, as it is essential to establish the underlying mechanisms driving changes in R&D activities. Only then can we begin to understand how firms mobilise resources and capabilities to respond and adapt to climate change-related challenges. Notably, our analysis not only highlights the importance of recognising climate change and its associated effects on SMEs, but also unveils the key climate challenges experienced by SMEs. Our second key contribution concerns the use of a novel measurement of climate change-related challenges. The novel data enables us to measure

the influence of different climate change-related challenges, and the mechanisms by which they affect SMEs in the context of Ireland.

Our findings highlight several takeaways, which can prove insightful for SMEs and policymakers alike. Our results suggest that SMEs could usefully focus more on building the capabilities and capacities necessary for R&D, to respond to climate change-related challenges. From a policy perspective, our findings may be potentially useful in future policy design focused on building policy supports, including R&D supports for SMEs (financial and non-financial supports). A clearer understanding of the mechanisms driving SMEs' R&D activities may help to guide policy-makers decisions on how best to design and target R&D supports for SMEs, especially in the context of increasing climate change-related challenges.

Despite key insights emanating from this exploratory study, it is not free from limitations. From our data, we can only observe how climate change-related challenges affect SMEs' R&D activities at a point in time. We advise caution when interpreting our results and to highlight that we cannot draw any causal inference. Instead, we encourage the interpretation of these results to act as a springboard for greater exploration and further empirical analysis of climate change-related challenges and R&D activities. In addition, from our data, we cannot ascertain that SMEs use R&D for the purpose of developing environmental innovations, or changes in internal organisational processes to become more environmentally friendly. It would be insightful for future studies to pay closer attention regarding the orientation of the SMEs' R&D. Moreover, the Irish landscape is the focus of this study. It would be beneficial to replicate this study across multiple countries and draw comparisons to suggest further insights and lessons learned. Finally, our study focuses on traditional or general R&D as opposed to 'Green R&D'. It would be fruitful for future studies (given data availability for robust measures of green R&D) to consider the effects of climate change-related challenges on both non-green and green R&D, and to explore either their substitutive or complementary relationships.

Despite the above limitations, our paper offers important and novel insights as to how climate change-related challenges may shape and reshape SMEs' R&D activities. In so doing, we offer important insights for firms and policymakers, as to the types of climate change challenges that may be most effective in influencing SMEs' R&D activities. As a result, firms and policymakers alike can be better prepared to adapt to and overcome climate change-related challenges.

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Supplementary Material

Table A1. Questions on Climate change-related challenges and firms' R&D activities in the IIE survey 2018-2020

Variables	Survey Question
Climate change-related challenges (i.e. in 2020)	'During 2018 to 2020, how important were the following factors related to climate change for your business?'
Regulatory/policy measures	Government policies or measures related to climate change (High-Medium-Low Importance, Not Relevant).
Consumer demand	Increasing customer demand for products that help mitigate or adapt to climate change (e.g. low-carbon products). (High-Medium-Low Importance, Not Relevant)
Extreme weather conditions	Impacts of extreme weather conditions (e.g. damages/disturbances). (High-Medium-Low Importance, Not Relevant).
Higher costs/input prices	'Increasing costs or input prices resulting from climate change (e.g. higher insurance fees, higher prices for water, adaptation of processes or facilities) (High-Medium-Low Importance, Not Relevant).
Dependent variables (i.e. in 2020)	
Invest in R&D	During the three years 2018 to 2020, did your enterprise engage in the following innovation activities: (1) In-House R&D; (2) External R&D; (3) All other innovations; and (4) None of the above
Continuous/occasional R&D	Did your enterprise perform R&D during the three years 2018 to 2020: (1) Continuously; (2) Occasionally

Note: For each of the four climate change-related challenges, they are measured as a binary variable = 1 if a firm places 'High' or 'Medium' Importance on the associated challenges, otherwise = 0.

Table B1. Correlation matrix for climate change-related challenges

	(1)	(2)	(3)	(4)
Regulations/Policy measures (1)	1.000			
Consumer demand (2)	0.660	1.000		
Extreme weather conditions (3)	0.368	0.370	1.000	
Higher costs/Input prices (4)	0.517	0.467	0.440	1.000

Table C1. Results of logit estimation used to obtain firms' propensity scores

Matching variables	**(1=Yes) Marginal Effects**	**(1=Yes) Marginal Effects**
Enterprise group	0.018	-0.156
	(0.086)	(0.229)
Domestic	-0.097***	-0.337***
	(0.028)	(0.101)
Average turnover (logarithm)	0.032	0.046
	(0.029)	(0.077)
Exports	-0.146*	-0.260***
	(0.057)	(0.001)
Invest in R&D (i.e. in 2018)	-0.126	-0.108
	(0.081)	(0.154)
Total innovation expenditure (logarithm)	-0.024**	-0.053
	(0.010)	(0.055)
Forward linkages	0.351***	0.552***
	(0.011)	(0.141)
Backward linkages	-0.125***	-0.022
	(0.012	(0.276)
Horizontal linkages	-0.233***	0.378*
	(0.017)	(0.215)
Public knowledge linkages	0.128***	-0.452**
	(0.035)	(0.202)
Financial obstacles	0.183**	0.484**
	(0.093)	(0.206)
Knowledge obstacles	0.001	-0.301***
	(0.066)	(0.032)
R&D tax credit	-0.069	-0.569*
	(0.306)	(0.298)
Firm Size (<50 employees)	0.132***	0.045
	(0.033)	(0.098)
Constant	0.490**	1.168
	(0.220)	(1.534)
Pseudo R^2	0.009	0.046
Log Likelihood	-1173	-352.7
No. of Obvs	1,708	539

Note: *** p < 0.01, ** p < 0.05, * p <0.1. Robust standard errors in parentheses. Coefficients are expressed as marginal effects. Where SMEs report 'High' or 'Medium' importance, the headline measure for climate change-related challenges is equal to 1, otherwise, it is equal to 0. Sector dummy variables for each category are included in the propensity score estimation, but are not reported here. Pseudo R^2 shows the overall variance explained by our model.

Table D1: NACE Rev. 2 Classification Sections used in the analysis

Sector B	Mining and Quarrying
Sector C	Manufacturing
Sector D	Electricity, Gas, etc.
Sector E	Water supply, etc.
Sector G	Wholesale and retail
Sector H	Transport and storage
Sector J	Information and comm.
Sector K	Financial services
Sector M	Scientific and technical act.

NACE is the acronym for 'nomenclature statistique des activités économiques dans la Communauté européenne', or statistical classification of economic activities in the European Community (Eurostat, 2008). The sector descriptions used are those specified by Ireland's Department of Enterprise, Trade and Employment (DETE) in a report on the Annual Business Survey of Economic Impact (ABSEI) survey (DETE 2022), which uses NACE Rev. 2 classifications.

Table E1: Sample balance check (1:3 nearest neighbour matching) for analysis of climate change-related challenges affecting SMEs' investment in R&D

Matching Variables	Climate change-related challenge (1=Yes)	Climate change-related challenge (0=No)	Diff	Standard Error
Enterprise group	0.311	0.307	0.003	0.022
Domestic	0.828	0.825	0.003	0.017
Average turnover (logarithm)	5.266	5.136	0.130	0.104
Exports	0.670	0.645	0.024	1.845
Invest in R&D	0.274	0.260	0.013	0.021
Total innovation expenditure (log.)	2.315	2.249	0.065	0.138
Forward linkages	0.183	0.177	0.005	0.018
Backward linkages	0.228	0.224	0.003	0.020
Horizontal linkages	0.110	0.105	0.004	0.015
Public knowledge linkages	0.159	0.152	0.007	0.017
Financial obstacles	0.520	0.515	0.005	0.024
Knowledge obstacles	0.453	0.440	0.013	0.024
R&D tax credit	0.107	0.108	-0.000	0.015
Sector C (Manufacturing)	0.348	0.337	0.011	0.000
Sector D (Electricity, Gas, etc.)	0.002	0.002	0.000	0.000
Sector E (Water Supply, etc.)	0.016	0.015	0.000	0.000
Sector G (Wholesale and retail)	0.195	0.198	-0.003	0.000
Sector H (Transport and storage)	0.095	0.104	-0.008	0.000
Sector J (Information and comm.)	0.130	0.139	-0.008	0.000
Sector K (Financial Services)	0.129	0.120	0.008	0.000
Sector M (Scientific and technical act.)	0.075	0.074	0.001	0.000
Firm Size (<50 employees)	0.602	0.588	0.013	0.023
			Rubins B = 10.2; MeanBias = 2.0; MedBias = 1.8; R = 1.00	

Note: *** p < 0.01, ** p < 0.05, * p <0.1. Firms were matched using the nearest neighbour (1:3) technique. The reference category for Firm sector is NACE Rev.2 Classification Section, B, 'Mining and Quarrying'. These variables are represented as factor variables. The coefficients for 'Diff' refer to the difference between the firms impacted and the firms not impacted by climate change-related challenges. The 'Standard Error' refers to the standard error of the mean difference. The bottom row presents the diagnostic tests. The Rubin's B score represents the standardised difference of means of a linear index of the propensity score in treated and control firms. The Rubin's R is the ratio of treated to matched non-treated variances of the propensity score index. Values below 25 for Rubin's B, and between 0.5 and 2 for Rubin's R, are usually accepted as indicating a sufficiently balanced sample, as per Rosenbaum and Rubin (1985).

Table E2: Sample balance check 3 (1:3 nearest neighbour matching) for analysis of climate change-related challenges affecting SMEs' engagement in continuous R&D

Matching Variables	Climate change-related challenge (1=Yes)	Climate change-related challenge (0=No)	Diff	Standard Error
Enterprise group	0.291	0.303	-0.011	0.040
Domestic	0.822	0.819	0.003	0.033
Average turnover (logarithm)	5.264	5.275	-0.011	0.194
Exports	0.693	0.742	-0.049	0.041
Invest in R&D	0.280	0.325	-0.045	0.040
Total innovation expenditure (logarithm)	2.268	2.508	-0.239	0.265
Forward linkages	0.202	0.199	0.003	0.034
Backward linkages	0.235	0.244	-0.011	0.036
Horizontal linkages	0.118	0.118	0.000	0.026
Public knowledge linkages	0.151	0.150	0.001	0.031
Financial obstacles	0.527	0.554	-0.027	0.044
Knowledge obstacles	0.446	0.458	-0.011	0.044
R&D tax credit	0.321	0.296	0.024	0.043
Sector C (Manufacturing)	0.402	0.420	-0.018	0.000
Sector D (Electricity, Gas, etc.)	0.000	0.000	0.000	0.000
Sector E (Water Supply, etc.)	0.018	0.015	0.002	0.000
Sector G (Wholesale and retail)	0.173	0.169	0.003	0.000
Sector H (Transport and storage)	0.099	0.091	0.008	0.000
Sector J (Information and comm.)	0.118	0.105	0.012	0.000
Sector K (Financial Services)	0.118	0.109	0.008	0000
Sector M (Scientific and technical act.)	0.062	0.077	-0.014	0.000
Firm Size (<50 employees)	0.616	0.642	-0.025	0.043
Rubins B = 20.8; MeanBias = 3.6; MedBias = 2.8; R = 0.87				

Note: *** p < 0.01, ** p < 0.05, * p <0.1. Firms were matched using the nearest neighbour (3) technique. The reference category for Firm sector is NACE Rev.2 Classification Section B, 'Mining and Quarrying'. These variables are represented as factor variables. The coefficients for 'Diff' refer to the difference between the firms impacted and the firms not impacted by climate change-related challenges. The 'Standard Error' refers to the standard error of the mean difference. The bottom row presents the diagnostic tests. The Rubin's B score represents the standardised difference of means of a linear index of the propensity score in treated and control firms. The Rubin's R is the ratio of treated to matched non-treated variances of the propensity score index. Values below 25 for Rubin's B, and between 0.5 and 2 for Rubin's R, are usually accepted as indicating a sufficiently balanced sample, as per Rosenbaum and Rubin (1985).

Table F1. Robustness check results obtained using an Entropy Balancing approach

Dependent variables	**(1)** Invest in R&D (Binary Variable)	**(2)** Invest in R&D (Binary Variable)	**(3)** Continuous R&D (Binary Variable)	**(4)** Continuous R&D (Binary Variable)
Climate change-related challenges	0.324***		0.147	
	(0.072)		(0.120)	
Regulations/Policy measures		0.150		0.064
		(0.104)		(0.039)
Consumer demand		0.304***		0.034
		(0.105)		(0.191)
Extreme weather conditions		-0.183*		-0.188***
		(0.098)		(0.058)
Higher costs/Input prices		0.202**		0.148***
		(0.094)		(0.051)
Controls	Yes	Yes	Yes	Yes
Observations	1,702	1,702	503	503

Note: *** p < 0.01, ** p < 0.05, * p <0.1. Robust standard errors are in parentheses. Results are obtained using entropy balancing and re-running our baseline models, using the ebalance command in STATA. The estimation results presented in Column 1 and Column 2 are obtained using entropy balance matching, followed by weighted probit regression. As entropy balancing assigns a continuous weight to all firms in the control group, unlike PSM, there is no need to discard any sample size (Hainmueller 2012). Controls are included but not reported.

Table G1. Robustness check results obtained using Interaction terms

Dependent variables	**(1)**	**(2)**
	Invest in R&D (Binary Variable)	Continuous R&D (Binary Variable)
Climate change-related challenges	0.269**	0.303
	(0.117)	(0.205)
Small-sized firm	-0.099	0.160
	(0.115)	(0.204)
Climate change-related challenges x Small-sized firm	0.089	-0.292
	(0.150)	(0.264)
Controls	Yes	Yes
Observations	1,619	480

Note: *** p < 0.01, ** p < 0.05, * p <0.1. Robust standard errors in parentheses. The results presented in Columns 1 and 2 are obtained using a probit regression model on the binary outcome variables. In both cases, the variable 'Climate change-related challenges' reports the effect of climate change-related challenges on medium-sized firms, which is our base category. The interaction term 'Climate change-related challenges X Small-sized firm' captures the effect of climate change-related challenges on the R&D activities of small-sized firms, when compared to the base category that is medium-sized firms (i.e. the difference). We report the difference in predicted probabilities to invest in R&D and engage in continuous R&D, between small or medium-sized firms experiencing climate change-related challenges.[8] The difference in predicted probability reported in Columns 1 and 2 is calculated for small firms experiencing climate change-related challenges and medium-sized firms experiencing climate change-related challenges. The standard error on the estimated interaction term is calculated using the Delta method (Ai and Norton 2003). Controls are included but not reported.

[8] As there are no marginal effects for interaction terms in non-linear models, we instead use the discrete difference in predicted probabilities between both groups of firms (i.e. small firms experiencing climate change-related challenges and medium-sized firms experiencing climate change-related challenges) (Greene 2010). As a result, we examine the effect of climate change-related challenges at different values of firm size.

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