Do Investors Care about Carbon Offsets?

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Abstract

We examine how investors respond to firms' carbon offset strategies in voluntary carbon markets. Following the retirement of carbon offsets, we find a positive market reaction, with a cumulative abnormal return of 1.1% over 15 trading days. This market response is driven by the quality of offsets rather than their quantity. High-quality offsets, such as removal offsets and recent vintages generate positive stock market reactions, whereas the quantity of offsets retired has no significant effect. Moreover, during periods of abnormal temperature changes, which amplify the salience of climate-related actions, firms are more likely to increase high-quality offset retirements. Our results are consistent with a signaling framework, where high-quality offsets serve as credible signals of a firm's genuine commitment to sustainability.

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1 Introduction

Understanding how investors perceive firms' sustainability strategies is critical for advancing sustainable finance and enhancing its credibility (Starks, 2023). However, the lack of standardized frameworks and the prevalence of inconsistent metrics, such as ESG indicators (Berg et al., 2022) and carbon disclosure scores, complicates the task of assessing firms' true environmental and social commitments. We address this challenge by focusing on carbon offsets in the voluntary carbon market, a relatively underexplored area. Carbon offsets are tradable certificates representing the reduction or removal of a specific amount of carbon dioxide or its equivalent. As a voluntary mechanism, these offsets exhibit significant heterogeneity in quality: high-quality offsets are seen to deliver verifiable, substantial environmental benefits, while low-quality offsets are often criticized for their limited and questionable impact on emissions reductions (West et al., 2023; Heal, 2024). This enables us to assess how the quality of sustainable finance initiatives influences investor behavior and shapes investment decisions.

Carbon offsets have emerged as an important tool for firms aiming to achieve net-zero emissions targets (Heal, 2022).[1] Globally, demand for carbon offsets has surged, with the voluntary carbon market (VCM) reaching \$2.4 billion in 2023, nearly five times its 2020 size. Such growth illustrates the willingness of firms to engage in voluntary initiatives to meet sustainability goals. Unlike emissions trading schemes (ETS), which are typically mandated by regulatory frameworks, participation in the voluntary carbon market is entirely discretionary. Firms engage in these markets as a matter of choice, often to demonstrate environmental responsibility, rather than to comply with legal obligations. But how do investors perceive these initiatives? On one hand, classical finance theory, which underscores firms' accountability to profit-maximizing shareholders, might interpret expenditures without immediate financial returns as value-eroding (Friedman, 1970). On the other hand, environmental responsibility has also been associated with enhanced profitability and firm value, suggesting that sustainability efforts might align with shareholder interests. In this study, we investigate whether investors value the retirement of carbon offsets and how these initiatives influence corporate behavior.

While carbon offsets are increasingly recognized for their importance, their implications remain largely underexplored. Complementary to the work of Kim et al. (2024), which uses hand-collected data to show how firms leverage carbon offsets to manage transition costs and enhance reputational benefits, we empirically examine investors' preferences for carbon offsets. Our study relies on transaction data from ESGpedia, a Singapore-based ESG data and technology platform. This dataset, which provides de-

[1] For example, Apple has utilized carbon offsets to support its net-zero commitment, pledging to cut emissions by 75% from 2015 levels by 2030, with the remainder balanced through high-quality removal projects. For more details, see "Apple's Carbon Removal Strategy", January 2024.

tailed information on disclosed beneficiaries, offers a comprehensive view of firms' carbon offset retirements from two leading registries—Gold Standard and Verra. Together, these registries dominate the voluntary carbon market, accounting for over 85% of its activity.

To assess the quality of carbon offset projects, we match this dataset with the Voluntary Registry Offsets Database using project names. The final dataset includes 8,709 retirement records from 2009 to 2022, of which 2,810 are by public firms. Formally, we define high-quality carbon offsets as those that are removal-based and recent.[2] Two key patterns stand out in the trends associated with the quality of carbon offset retirements. First, while the demand for carbon offsets has grown substantially over time, the proportion of removal carbon offsets has remained stable. Second, while carbon offset retirements are particularly prominent in countries like the United States and Australia, firms in these regions tend to retire a smaller proportion of high-quality offsets relative to their total retired offsets. These observations underscore a gap between the quantity of offsets retired and their quality.

How do investors respond to carbon offsets? Their interpretation may fall into two opposing perspectives. On one hand, carbon offsets could signal a firm's genuine commitment to reducing its environmental footprint and achieving long-term sustainability. On the other hand, they may be dismissed as greenwashing, which are actions designed to create the appearance of environmental responsibility without delivering meaningful impact. To examine these possibilities, we analyze stock price reactions to the retirement of carbon offsets. If the credible signaling hypothesis holds, stock prices should rise, reflecting investor confidence in the firm's sustainability efforts. Conversely, if the greenwashing hypothesis prevails, stock prices are expected to remain unchanged, indicating investor skepticism.

In our benchmark analysis, we use an event study methodology to investigate how the stock market reacts to the retirement of carbon offsets. We find a positive market response, with a cumulative abnormal return (CAR) of 1.126% over the 15 trading days following the retirement event. These findings suggest that investors value carbon offsets. Consistent with prior research documenting positive stock market reactions to environmentally friendly corporate behavior (e.g., Klassen and McLaughlin, 1996; Flammer, 2013; Krüger, 2015; Garel et al., 2024), the overall positive response from investors suggests that they perceive carbon offset retirements as beneficial signals of the firm's reputation and sustainability commitments. But are all carbon offsets viewed equally? Could the perceived quality influence how investors response to them?

[2] The Voluntary Registry Offsets Database categorizes projects into reductions, impermanent removals, long-duration removals, and mixed. For our analysis, we classify projects as either reduction or removal, grouping all non-reduction projects under the removal category. Carbon offsets are considered recent if the gap between their retirement date and vintage date is less than or equal to the median value of 5 years.

A closer examination reveals that the positive stock market response is largely driven by high-quality carbon credits, such as removal offsets and those with recent vintage years. These offsets are generally viewed as more credible and impactful, directly addressing greenhouse gas emissions and aligning with investor expectations for genuine sustainability efforts. By contrast, we find no evidence of increased cumulative returns for low-quality offsets, including reduction offsets and those with older vintages. Specifically, the retirement of removal offsets yields a CAR of 1.941%, compared to 0.879% for the retirement of reduction offsets. Similarly, the retirement of offsets with recent vintages shows a CAR of 1.221%, outperforming the retirement of past vintage offsets, which exhibits a CAR of 0.972%. These findings underscore the importance of the underlying characteristics of carbon offsets, as investors are able to distinguish between different types of carbon credits. High-quality offsets act as credible signals, bolstering the firm's reputation and affirming its sustainability commitments, whereas low-quality offsets are dismissed as superficial, aligning with perceptions of greenwashing.

Furthermore, our analysis reveals that investors prioritize the quality of carbon offsets over their quantity. Changes in the volume of offsets retired show no statistically significant impact on stock returns, suggesting that the market is less influenced by the scale of offset activities. A plausible explanation is that larger volumes are often associated with lower-quality projects, which may fail to align with long-term sustainability objectives or raise doubts about the firm's authenticity (Trencher et al., 2024). This finding shows that investors emphasize substance over scale when evaluating environmental practices. Investors appear to scrutinize the credibility and impact of offset projects rather than simply rewarding firms for the volume of offsets retired. Consistent with prior research, our findings reinforce the idea that firms engaging in genuinely impactful environmental practices are more likely to gain investor approval (e.g., Flammer, 2021).

Our results remain robust across a range of potential concerns, ensuring the reliability of our findings. Specifically, to address concerns regarding the market model, we incorporate other priced factors, country-specific indices, and industry-specific trends. We also check the robustness of our CAR estimates by using precision-weighted averages and alternative specifications of standard errors. To further mitigate the influence of financial factors on our findings, we exclude firms from countries offering subsidies for carbon offset retirements and omit firms announcing financial events—such as equity or bond issuances or financial report releases—within the benchmark event window. These ensure that our results are not confounded by the firms' financial performance. In addition, we vary our event window to mitigate concerns about pre-release information and the choice of duration. Finally, we expand our sample by including omitted retirement dates to control for external influences. Collectively, these robustness checks reinforce the validity of our conclusions.

To further validate investors' preferences for carbon offsets, we examine the relationship between temperature anomalies and carbon offset demand. Prior research demonstrates that public concerns about climate change intensify during extreme weather events, leading to an increase in investors' preferences for "green" initiatives (Pástor et al., 2021; Ardia et al., 2023). In response, firms may strategically adjust their environmental practices to align with these preferences by appealing to sustainability-conscious investors. If investors indeed prioritize high-quality offsets, companies are expected to respond by retiring more high-quality carbon offsets during periods of extreme temperature, which act as a proxy for heightened climate change concerns (Herrnstadt and Muehlegger, 2014). To ensure temperature anomalies serve as a valid proxy for climate change beliefs, we also control for a set of co-variates identified in the literature such as GDP per capita (e.g, Dell et al., 2012), urbanization (e.g., Marchiori et al., 2012), carbon pricing policies (Liao and Junco, 2022), CO2 emissions (Lehr and Rehdanz, 2024).

Our findings suggest that investors place greater emphasis on the quality of carbon offsets rather than their quantity, particularly during periods of heightened climate concerns. Specifically, we observe a weak inverted-U relationship between temperature anomalies and overall carbon offset demand, indicating that companies reduce the total volume of retired offsets during extreme weather events. This behavior can be attributed to the perception that, as climate concerns intensify, investors view offset volume as a less credible signal of environmental commitment. Instead, the focus shifts toward the quality of offsets. Supporting this shift, we identify a U-shaped relationship between temperature anomalies and the demand for removal offsets and those with recent vintages. During periods of extreme temperatures, companies strategically increase the retirement of these high-quality offsets, which offer verifiable environmental benefits. The pattern reflects a deliberate response to heightened investor scrutiny, as firms aim to signal sustainability commitments by prioritizing offsets that are more credible and impactful.

This documented behavior aligns with the notion that firms anticipate greater investor expectations during extreme temperatures and respond by strategically retiring higher-quality offsets. These findings reinforce the argument that investors prioritize the credibility and environmental impact of offsets over their sheer volume. To ensure the robustness of these conclusions, we conducted several robustness checks, including the use of alternative temperature datasets and different fixed-effects specifications, both of which confirmed the consistency of our results. Furthermore, to address concerns about the external validity of investor preferences, we expanded our analysis to include all offset beneficiaries, such as governments, individuals, and non-profits. The results from this broader sample aligned closely with our initial findings, further strengthening the robustness and generalizability of our conclusions. Together, these insights underscore the pivotal role of offset quality in shaping firm behavior and investor perceptions during periods of heightened climate concern.

We then demonstrate that our empirical findings can be theoretically explained through a simple signaling game. In this model, a firm decides how to allocate its fixed budget between retiring a small number of high-quality carbon offsets or a large volume of low-quality offsets. The firm's choice acts as a signal that is observed by a green investor. The investor then updates the beliefs about whether the firm is genuinely committed to environmental sustainability (green) or merely engaging in greenwashing (brown). These updated beliefs, in turn, influence the investor's decision on whether to allocate investments to the firm.

By solving the game, we first identify a separating equilibrium in which green firms signal authenticity by retiring high-quality offsets. This strategy credibly conveys their commitment to sustainability, prompting investors to interpret these actions as genuine and encouraging investment. In contrast, brown firms, constrained by the cost of high-quality offsets and their limited focus on reputation, favor low-quality offsets that fail to elicit positive investor responses. The model also identifies a pooling equilibrium under heightened climate change concerns. In this scenario, both green and brown firms retire high-quality offsets as they anticipate greater reputation benefits driven by increased investor willingness to pay for credible environmental actions. This equilibrium reflects a strategic shift where firms prioritize offset quality to capitalize on evolving investor preferences, aligning actions across firm types.

Our theoretical insights align closely with the empirical findings, emphasizing the critical role of offset quality in shaping investor decisions. High-quality offsets serve as credible signals of environmental commitment, especially during periods of heightened climate awareness, and are often linked to favorable stock price performance. As a result, green firms are incentivized to prioritize offset quality, aligning with investor preferences and enhancing market valuation. Conversely, low-quality offsets fail to effectively attract positive investor responses, underscoring their limited influence in driving market appeal.

1.1 Related Literature

This paper contributes to several strands of literature. First, it adds to the literature on the voluntary carbon market (VCM). While the environmental effectiveness of the VCM has been well examined in the literature (Groom et al., 2022; Trencher et al., 2024; Swinfield et al., 2024; Calel et al., 2025), its economic implications remain relatively underexplored. Relevant studies in this area include Diederich and Goeschl (2018), which finds no locational preferences in VCM participation, and Engler et al. (2023), which investigates the factors influencing voluntary CO2 offsetting by small- and medium-sized enterprises in Germany. Our study is most closely related to Kim et al. (2024), which examines the incentives for retiring carbon offsets from a company's perspective. Using an exogenous ESG rating shock, they demonstrate that firms use carbon offsets to either outsource transition efforts or achieve ranking benefits. We distinguish our work by focusing on the investor's perspective. Specifically, we analyze how the stock market responds to carbon offset retirements and how firms adjust their actions to align with investor preferences, particularly during periods of heightened climate change concerns.

Next, this study is related to the literature on the relationship between companies' environmental responsibility and stock market performance. Prior research has highlighted a positive relationship between stock market performance and corporate environmental commitment. Examples include reduced carbon emissions (Bolton and Kacperczyk, 2021; Aswani et al., 2024), biodiversity preservation (Garel et al., 2024), green bond issuance (Tang and Zhang, 2020; Flammer, 2021), announcements of environmentally related corporate initiatives (Flammer, 2013), increasing sustainability ranking (Hartzmark and Sussman, 2019). Our paper contributes to the growing body of research linking corporate environmental actions to stock market performance. Using an event study methodology, we show that the stock market responds positively to companies' voluntary carbon offset retirements, with the quality of the offsets playing a critical role in shaping investor reactions.

Finally, we contribute to the literature exploring the economic effects of temperature. Prior studies have shown that temperature anomalies significantly influence macroeconomic outcomes, such as GDP (Dell et al., 2012; Newell et al., 2021; Bilal and Känzig, 2024), migration patterns (Marchiori et al., 2012; Cattaneo and Peri, 2016), the implementation of climate policies (Liao and Junco, 2022), CO2 emissions (Lehr and Rehdanz, 2024), green investment (Anderson and Robinson, 2024), and public awareness of climate change (Herrnstadt and Muehlegger, 2014; Burke and Emerick, 2016; Choi et al., 2020). This paper complements prior research by emphasizing how temperature anomalies influence corporate demand for carbon offsets. We establish a novel connection between temperature anomalies, heightened awareness of climate change, and companies' voluntary environmental engagement.

The remainder of the paper is organized as follows. Section 2 provides an institutional overview of the voluntary carbon market and explores potential investor perceptions of carbon offset retirements. Section 3 describes the data on carbon offset retirements and presents key stylized facts. Section 4 examines stock market reactions to carbon offset retirements. In Section 5, we investigate the effects of temperature anomalies on carbon offset demand. Section 6 presents a signaling model that theoretically reconciles our empirical findings on investors' preferences and firms' behavior. Finally, Section 7 offers concluding remarks.

2 Background and Conceptual Framework

This section first introduces the institutional background of the voluntary carbon market, where carbon offsets are traded, and provides an overview of carbon offsets themselves. Next, we discuss the conceptual framework of investors' perceptions on carbon offsets.

2.1 Voluntary Carbon Market

The voluntary carbon market (VCM) emerged in the early 1990s in response to growing climate awareness, as firms voluntarily began offsetting their emissions to support sustainability efforts. Initially modest in scale, the market relied predominantly on unregulated reforestation projects as sources of carbon offsets. However, by the early 2000s, escalating concerns about climate change led to the establishment of frameworks aimed at enhancing the market's credibility and transparency. Organizations such as the Gold Standard (founded in 2003) and Verra (formerly the Verified Carbon Standard, launched in 2005) played pivotal roles in formalizing and strengthening the integrity of the VCM.

Today, the VCM facilitates the trading of carbon offsets among companies, nonprofit organizations, governments, and individuals. These carbon offsets, also known as voluntary carbon credits, are tradable certificates representing the reduction or removal of one metric ton of carbon dioxide or its equivalent in other greenhouse gases. They have become a vital tool in combating climate change, enabling entities to compensate for their emissions by supporting verified projects that mitigate greenhouse gases. For organizations unable to fully meet their emission reduction targets, offsets provide a practical solution to bridge the gap. For example, an airline aiming for carbon neutrality might calculate its unavoidable emissions and purchase offsets by funding a reforestation project in Colombia. To better understand the carbon offset process, we illustrate the structured timeline in Figure 1.

< Insert Figure 1 here >

Each offset is tied to a specific vintage, which represents the period during which the associated carbon reduction or removal occurred, defined by its start and end dates. Once the vintage period concludes, certifying organizations such as Verra and Gold Standard assess whether the projects meet stringent standards. Upon approval, the offsets are issued as tradable assets on the VCM. These assets can be traded until they are retired. The retirement of carbon offsets is a critical step in ensuring transparency and preventing double counting. Once retired, offsets are permanently removed from circulation, reflecting their final use and underlying demand. Retirement also signifies an organization's tangible commitment to offsetting emissions. For instance, an airline can credibly claim carbon neutrality only after officially retiring offsets, demonstrating its support for verified carbon reduction or removal efforts. This process underscores how retirement preserves the integrity and credibility of the carbon offset market.

In this study, we focus on carbon offset retirements to analyze investor responses for several key reasons. First, retirements are promptly recorded in carbon registries, providing clear and verifiable timestamps. In contrast, firms rarely disclose when they purchase carbon offsets. Since offsets remain tradable until retired, companies can hold them as part of their carbon management strategies or financial portfolios, retaining the option to sell them later. Moreover, firms seldom pre-announce specific retirement dates, instead emphasizing retirements in sustainability reports or public announcements to mark significant milestones in their carbon reduction strategies. Finally, retirement represents the decisive step in creating a direct environmental impact. Only through retirement can a company officially offset its emissions, fulfilling its commitments to carbon neutrality or net-zero targets.

To be clear, the VCM operates independently of compliance markets such as EU Emissions Trading System, allowing participants to engage in emission reductions or removals on a voluntary basis.[3] Unlike cap-and-trade systems, which have a limited supply of allowances, the VCM adopts a project-based approach that offers a more flexible framework for participation. Companies participate in the VCM for various reasons: a sense of environmental responsibility, pressure from shareholders, or as part of a public relations strategy. Additionally, the VCM enables firms to outsource their transition efforts by purchasing carbon offsets rather than directly investing in abatement technologies.[4] As businesses intensify efforts to achieve carbon neutrality, these factors have driven the carbon offset market's growth, surpassing US$1 billion in value by 2021.

However, this rapid expansion has not been without challenges. Carbon offsets are fundamentally heterogeneous, differing widely in their characteristics and impact. Criticism over inconsistent standards and doubts about the actual impact of certain offsets (e.g., Trencher et al. (2024) have raised concerns about the market's credibility). In response, initiatives to enhance regulation and standardization are gaining momentum,

[3]There are several exceptions. For example, the California Air Resources Board (CARB), until 2015, permitted the use of certain voluntary offsets in the California Cap-and-Trade program under the Early Action Offset Program, provided they adhered to specified quantification methodologies and restrictions. Similarly, the EU Emissions Trading System (EU ETS) allowed limited use of offsets aligned with Kyoto Protocol mechanisms until 2020. However, the carbon offset retirements analyzed in this study are unrelated to these regulatory programs.

[4]For example, the 2023 Amazon Sustainability Report states: "In parallel to reducing and avoiding emissions throughout our business, we are also investing in carbon neutralization through additional, quantifiable, real, permanent, and socially beneficial offsets." Similarly, Microsoft highlights its commitment to becoming carbon negative, stating, "Microsoft's commitment to become carbon negative will require us to purchase an increasing amount of carbon removal." For more details, see "Microsoft Environmental Sustainability Report 2020".

aiming to ensure that voluntary offsets contribute meaningfully to emissions reductions and removals (Pande, 2024). As the focus shifts to offset quality, evaluations increasingly emphasize environmental impact and credibility. To assess quality, two critical dimensions stand out: the type of offsets and their vintage.

Carbon offsets can be broadly categorized into two primary types: reduction (or avoidance) and removal.[5] Reduction projects aim to prevent emissions through initiatives such as renewable energy adoption or conservation programs, including REDD+ forestry projects designed to curb deforestation. While these projects contribute to emissions avoidance, they have faced criticism for delivering limited, often unverifiable, environmental benefits (Groom et al., 2022; West et al., 2023). In contrast, removal projects directly extract carbon dioxide from the atmosphere, making them inherently more impactful. These projects encompass nature-based solutions, such as reforestation, which leverage natural systems, and technology-driven approaches, like direct air capture, which use engineered techniques. Their ability to deliver measurable and lasting climate benefits makes them especially valuable for achieving long-term, net-negative emissions goals (Swinfield et al., 2024; Heal, 2024). As a result, offsets from removal projects are traded at a clear premium. On average, their prices are approximately three times higher than those of offsets from reduction projects.[6]

Alongside project type, the vintage of an offset, which is the year the emissions reduction or removal occurred, is another key indicator for quality. Older vintages often fall short of contemporary standards for additionality and verification, raising concerns about their reliability and effectiveness (e.g., Trencher et al., 2024). In contrast, offsets with more recent vintages are generally preferred due to their alignment with updated climate goals and methodologies, ensuring greater transparency and compliance with current standards. This preference is reflected in market prices, where newer offsets selling for higher prices. Therefore, we define high-quality carbon offsets as those originating from removal projects and those with recent vintages. These attributes ensure that the offsets provide tangible, measurable climate benefits while meeting growing expectations for credibility and effectiveness.

2.2 Conceptual Framework

We now turn to investors' preferences, which may be shaped by two contrasting perceptions. On one hand, investors might view the retirement of carbon offsets as a credible signal of a firm's genuine commitment to environmental sustainability. On the other

[5] For a comprehensive overview of project types across major carbon registries, see "Voluntary Registry Offsets Database", Berkeley Carbon Trading Project, University of California, Berkeley.

[6] For detailed price differentiation across offset categories, see "State and Trends of Carbon Pricing 2023", World Bank.

hand, they may suspect that companies use carbon offsets as a greenwashing tool, retiring offsets with limited environmental benefits.

2.2.1 Credible Signaling

The voluntary retirement of carbon offsets can be understood through the lens of signaling theory, as firms use this action to credibly convey their environmental commitment to investors. In sustainable finance, investors often face uncertainty about firms' actual environmental practices (e.g., Avramov et al., 2022) and have limited information to assess these commitments (e.g., Lyon and Maxwell, 2011). This information asymmetry imposes transaction costs on identifying genuinely sustainable firms (e.g., Akerlof, 1970). Therefore, firms have an incentive to reduce asymmetry by signaling-that is, taking actions that credibly communicate their environmental dedication, helping investors distinguish between genuinely committed firms and others.

By retiring carbon offsets, firms can signal their commitment toward the environment. This signal tend to be credible for the following reasons. First, it is measurable for firms' commitment when retiring carbon offsets. One unit of carbon offsets represents for the equivalent of one metric tonne of CO2 reduced or removed. Therefore, investors can quantify the environmental dedication of firms by the amount of carbon offsets retired. Second, carbon offset retirement involves transparency and accountability. Upon retirement, companies allow stakeholders (such as investors, customers, and environmental watchdogs) to scrutinize their offsets. For instance, many companies provide access to retirement records on registries (e.g., Verra or Gold Standard) that list details such as the project name, location, carbon reduction or removal method, and verification standards. This transparency reduces doubts about the legitimacy of the offset and discourages any double-counting or resale of offsets.

The primary testable implication of credible signaling is that investors respond positively to firms' eco-friendly actions. Past event studies have documented positive abnormal returns in response to companies' environmentally responsible behavior (e.g., Flammer, 2013; Krüger, 2015; Garel et al., 2024). Relevant to this study, Flammer (2021) finds that corporate green bond issuance generates favorable stock market reactions, as they effectively signal a firm's commitment to environmental sustainability. Thus, if investors perceive that retiring carbon offsets credibly signals a firm's environmental commitment, we would expect a positive stock market reaction to such retirements.

To further investigate the role of signaling, we examine the relationship between firms' carbon offset retirements and public beliefs about climate change. As noted, firms signal their environmental commitment to enhance their "green" reputation and reap associated benefits. When public concerns about climate change intensify, the advantages of being perceived as environmentally responsible grow (Pástor et al., 2021; Ardia et al., 2023). This amplifies the cost of information asymmetry between investors and firms regarding environmental commitments. If investors value carbon offsets, firms have a stronger incentive to retire such offsets as credible signals of genuine climate action. Conversely, if these offsets hold little appeal to investors, firms face limited motivation to adjust their practices, even during periods of heightened climate concerns. To examine how climate change beliefs influence carbon credit demand, we use temperature anomalies as a proxy for these beliefs (Herrnstadt and Muehlegger, 2014; Burke and Emerick, 2016; Choi et al., 2020). If the credible signaling channel holds, we hypothesize that periods of extreme temperature will result in greater demand for carbon offsets, as heightened climate awareness increases the value placed on credible environmental commitments.

2.2.2 Greenwashing

Another perspective investors may hold about carbon offset retirements is that they represent a form of greenwashing. Greenwashing, the practice of making false or exaggerated claims about a company's sustainability efforts, is a widespread concern (e.g., Marquis et al., 2016; Berrone et al., 2017). Companies may engage in tactics such as selective disclosure, the use of dubious eco-labels, and crafting deceptive narratives about their environmental initiatives (see Lyon and Montgomery (2015) for a detailed review).

In the emerging voluntary carbon offset market, greenwashing presents significant challenges because it undermines trust and transparency. Some firms may intentionally misrepresent their environmental commitments by overstating the impact of their carbon offset initiatives or by retiring offsets from projects that provide minimal or unverifiable environmental benefits. This misrepresentation can deceive stakeholders, including investors and consumers, into believing that these firms are taking meaningful climate action when, in reality, their efforts may be superficial or ineffective. Such practices erode the credibility of the voluntary carbon market, making it harder for genuinely committed firms to distinguish themselves. Moreover, greenwashing can reduce the market's overall effectiveness in combating climate change, as resources may be diverted toward projects that fail to deliver measurable or lasting carbon reductions.

The implications of greenwashing perceptions for stock market returns differ sharply from scenarios where carbon offsets are seen as credible signals. If investors view carbon offsets as a form of greenwashing, the stock market is likely to exhibit either no significant reaction or a negative response to offset retirements. Thus, carbon offset retirements play a pivotal role in shaping investor perceptions. When viewed as genuine efforts, they signal a firm's authentic commitment to environmental sustainability, boosting confidence and driving positive market reactions. Conversely, if perceived as greenwashing, they erode trust, casting doubt on the firm's credibility and the efficacy of its environmental initiatives. This contrast underscores the need to understand how firms' offset strategies resonate with investor sentiment.

3 Data

In this paper, we rely on carbon offset transaction data from the ESGpedia platform, which tracks firms' retirement of offsets from two major carbon registries: Gold Standard and Verra. ESGpedia, developed by STACS, is a digital platform for ESG data and solutions across Asia-Pacific, enabling companies and financial institutions to achieve ESG goals. Our full dataset contains more than 260,000 entries of voluntary carbon offset retirement records from 2009 to 2022.

We refine our sample by excluding carbon offset retirements with undisclosed beneficiaries. The remaining data is merged with country-level variables, including temperature, precipitation, GDP per capita, urbanization, emissions per capita, and carbon pricing policies. Carbon offset project types are then classified by matching the data with the Voluntary Registry Offsets Database. This process produces a final dataset of 8,709 carbon offset retirement records from 2009 to 2022, consisting of 2,810 retirements by public firms and 5,899 by other entities, such as governments, private firms, and non-profit organizations. Our analysis focuses on the 2,810 public firm retirements, examining their impact on investor behavior.

3.1 Summary Statistics

Table 1 provides summary statistics on carbon offset retirement transactions by public firms. Panel A presents information of the carbon offsets obtained from ESGpedia. Here, we find that the amount of retired carbon offsets varies significantly across transactions. Among the 2,810 retirement transactions, the average retired amount of each transaction is 19,675 offsets. The vintage duration, defined as the time between the start and end dates of emissions reductions or removals, averages 435 days. The verification duration, which refers to the period required for registry validation, averages approximately 3 years (1,079 days).[7] Once issued, carbon offsets can be freely traded on the market until retirement. The average trading duration, which is the time between issuance and retirement, is about 553 days.

[7] A negative verification duration suggests that the issuance date of carbon offsets may precede the vintage end date. This happens when project developers apply for issuance based on interim data or partial completion of the vintage period. If they can demonstrate that quantifiable emissions reductions or removals have been achieved, they may request issuance even before the entire vintage period concludes.

< Insert Table 1 here >

We then turn to the classification of carbon offsets. As highlighted earlier, high-quality carbon offsets are defined as those associated with removal projects and recent vintages. We begin by examining removal projects. Based on the Voluntary Registry Offsets Database, 24% of retired offset transactions fall under the removal category.[8] The remaining 76% are classified as reduction projects. Turning to vintages, we classify carbon offsets as "recent" if the difference between the retirement year and the vintage start year is five years or less. This threshold aligns with the median value in our sample and captures offsets reflecting relatively recent emission reduction or removal activities.[9] In our dataset, 60% of carbon offset retirements involve recent vintages, indicating a clear preference for newer offsets.

We also consider the geographical origin of carbon offsets, focusing on domestic offsets, which are those generated through emissions reduction or removal projects within the same country as the beneficiary firm. This classification underscores the localized aspect of carbon mitigation efforts. However, only 4% of retired offsets are derived from domestic projects, highlighting firms' heavy reliance on international offsets over those produced within their home countries.

In Panel B, we turn to the country-by-year-level variables. Drawing on data from Our World in Data, we observe that the average temperature anomaly across these countries is 0.510 degrees Celsius, measured as the deviation from the 1991–2020 mean. The average rainfall anomaly is found to be 17.449 mm.[10] Economic indicators reveal that GDP per capita, adjusted for inflation and cross-country cost of living differences, averages $46,579. Urbanization, defined as the proportion of the population residing in urban areas, has a mean of approximately 84%. CO_2 emissions per capita, calculated as total emissions divided by population, average 11 tonnes per person in this sample. Finally, 76.4% of carbon offset retirements occur in countries with Emissions Trading System (ETS) policies, while 26.7% are from countries implementing a carbon tax.[11]

[8] Offsets labeled as "mixed type" in the database are also included in the "removal" category for consistency.

[9] Summary statistics indicate that the average vintage duration is approximately one year, typically spanning from the beginning to the end of a calendar year. Consequently, using the vintage start year closely approximates calculations based on the vintage end year.

[10] Precipitation data is obtained from the Climate Change Knowledge Portal, World Bank, which also provides temperature data used for robustness checks in the following section.

[11] Summary statistics for retirements across all beneficiaries, including non-public firms, are provided in Table B.1. These results indicate that most variables are comparable to those of public firms, except that non-public firms retire a smaller average volume of carbon offsets.

3.2 Carbon Offset Retirements over Time and Space

To explore trends in carbon offset retirements, we begin by aggregating offsets by their retirement year. Figure 2 presents the evolution of retired carbon offsets over time, with blue and orange bars representing annual totals for all retired offsets and retired removal offsets, respectively. Here, we find that there is a significant rise in both total retired offsets and removal offsets from 2009 to 2022. In Table B.2 in the online appendix, we show that total retired offsets surged from 47,089 in 2009 to approximately 20 million in 2022. Removal offsets, absent in 2009, reached over 3 million by 2022, representing roughly 17% of total retirements. This rapid growth underscores the increasing importance of corporate environmental commitments, spurred by sustainable finance initiatives and alignment with the Paris Agreement's climate goals. However, the relatively lower share of removal offsets highlights the limited demand for high-quality carbon offset projects within the voluntary carbon market.

< Insert Figure 2 here >

We then turn to geographic patterns in carbon offset retirements in Figure 3. There are two panels. Panel (a) maps the total volume of retired offsets by country, while Panel (b) displays the share of removal offsets relative to total offsets. Darker shades in each panel correspond to higher values, indicating regional variations in the volume and quality of carbon offset retirements.

< Insert Figure 3 here >

Panel (a) reveals that carbon offset retirements are heavily concentrated in countries such as the United States and Australia. However, as shown in Panel (b), firms in these countries retire a relatively smaller proportion of removal offsets compared to their total retirements. In contrast, the share of removal offsets is notably higher in regions like Europe and South America. This pattern is further supported by Table B.3 in the online appendix, which shows that only 2% of offsets retired by Australian firms and 15.3% by U.S. firms are removal projects. In comparison, removal offsets account for approximately 30% of retirements in countries such as Denmark and Egypt. Thus, there are substantial regional differences in firms' preferences for carbon offset project types.

4 Stock Market Impact of Carbon Offset Retirements

We now turn to our main analysis. Do investors value carbon offsets, and how do they reflect them in firm valuations? To explore these questions, we analyze the stock market's reaction to carbon offset retirement announcements using an event study methodology.

4.1 Event Study Methodology

In our event study, we define the carbon offset retirement date as the event date. Firms retire carbon offsets through recognized registries such as Verra or Gold Standard, which publicly record detailed information about each retirement. These registries provide comprehensive and precise data, including the retirement date and the originating project for the offsets, ensuring a clear and well-defined event timeline. While some firms may omit specific retirement dates in their sustainability or financial reports, these registries offer investors consistent and reliable access to accurate retirement information.

Following the event study methodology used in Flammer (2021), which investigates the impact of green bond announcements on stock market prices, we employ a 16-trading-day window to capture potential investor responses. Our baseline event window is defined as [0, 15], excluding pre-event trading days. This approach reflects the fact that firms typically do not pre-announce carbon offset retirement dates, and investors only access this information through carbon registries after the official retirement. Consequently, immediate pre-announcement trading is unlikely. To account for potential delays in investor awareness and reaction, we also extend our analysis to include longer post-event periods. It is possible that the extended post-event duration may capture confounding events, such as financial report releases or bond issuances, which could bias our estimates. To address this concern, we conduct robustness checks detailed in a later section. Additionally, we examine the pre-event intervals [–20, –11] and [–10, –1], as well as the post-event intervals [16, 30] and [31, 60], to assess potential stock price run-ups or trends surrounding the event window.

Our stock market data are collected from the daily stock file of Compustat. For each firm i, we calculate the abnormal returns using the market model. The coefficients α_i and β_i of the model are estimated using daily return data within a estimation window of 200 trading days ([–220, –21]) prior to the first event window. Formally, the ordinary least squares (OLS) market model is:

$$R_{it} = \alpha_i + \beta_i \times GlobalIndex_t + \epsilon_{it} \tag{1}$$

where R_{it} is the stock return of firm i on day t, $GlobalIndex_t$ is the daily market return, and ϵ_{it} is the error term. For the market return, we use a global stock market index (the MSCI All Country World Equity Index) in our baseline model. In robustness checks, we show that our results are robust if using country-specific stock market indices.

The estimated stock return of firm i on day t can be obtained with estimated market model parameters $\hat{\alpha}_i$, $\hat{\beta}_i$ and the global market index as follows:

$$\hat{R}_{it} = \hat{\alpha}_i + \hat{\beta}_i \times GlobalIndex_t \tag{2}$$

Subsequently, the abnormal daily return (AR) of firm i on day t can be calculated as follows:

$$AR_{it} = R_{it} - \hat{R}_{it} \tag{3}$$

Finally, cumulative abnormal returns (CARs) are calculated for each specified time interval by summing the abnormal returns within those windows. The CARs are reported for the following intervals: [–20, –11], [–10, –1], [16, 30], and [31, 60], in addition to the event window [0, 15].

4.2 Event Study Results

Our baseline analysis examines the returns of common stocks from 205 public firms associated with 236 carbon offset retirement events. To ensure a clean estimation and well-defined post-event window, we limit the sample to firms with accessible common stock price data surrounding their retirement dates and exclude firms with frequent offset retirements. Specifically, for each retirement event, we require a minimum gap of 280 trading days (approximately 400 calendar days) before the preceding retirement and at least 60 trading days (around 80 calendar days) afterward. These criteria are designed to isolate the impact of each carbon offset retirement on the firm's stock performance, minimizing confounding effects from overlapping events.

Table 2 presents the baseline results from the event study. The analysis is based on a restricted sample of 236 retiree-date observations. For each event window, the average cumulative abnormal return (CAR) is expressed as a percentage. Importantly, the average CAR for the event window $[0, 15]$ is 1.126%, which is statistically significant at the 5% level. In contrast, CARs for all other time windows, both preceding and following this event window, are statistically insignificant, suggesting that the observed effect is not driven by unrelated trends surrounding the retirement date.

< Insert Table 2 here >

The positive average CAR implies a favorable stock market response to carbon offset retirements, with these firms' stock prices exceeding market expectations by 1.126% in the 15 trading days following the event. This finding indicates that investors value carbon offset retirements, potentially viewing them as credible signals of a firm's commitment to sustainability and its positive impact on reputation. These results are consistent with prior research demonstrating that corporate eco-friendly actions tend to generate positive CARs (e.g., Flammer, 2013; Krüger, 2015; Garel et al., 2024).

We now turn our attention to the quality of carbon offsets. Here, one important attribute is the type of carbon offset. In Panel A of Table 3, we compare the stock market's response to the retirement of removal offsets versus reduction offsets. In some cases, firms may retire both removal and reduction offsets on the same day. To ensure clarity in classification, we label a retirement date as a "removal offset retirement" if removal offsets are included among the offsets retired that day, as these offsets are considered higher quality and more impactful. Our findings reveal that the stock market reaction to removal offset retirements is both larger and statistically significant, whereas the reaction to reduction offset retirements is smaller and statistically insignificant. Specifically, the cumulative abnormal return (CAR) following the retirement of removal offsets is 1.941% (statistically significant at the 5% level), compared to 0.879% for reduction offsets (statistically insignificant at the 10% level).

These results indicate that investors place greater value on removal carbon offsets than on reduction offsets As highlighted in Section 2, removal offsets are generated from high-quality projects such as agriculture, forestry, and other land use (AFOLU), carbon capture and storage (CCS), and afforestation/reforestation (A/R). These offsets typically command a premium in the market relative to reduction offsets. Consequently, the retirement of removal offsets provides a more credible signal of a firm's commitment to environmental sustainability, capturing greater investor attention.

< Insert Table 3 here >

In Panel B, we explore the recency effect by comparing the retirement of recent carbon offsets to that of older offsets. Since a firm may retire multiple offsets on the same day, we calculate the average gap between the retirement year and the vintage start year at the firm-date level. As defined earlier, we categorize an offset as recent if this gap is less than or equal to five years. The results show out that investors respond more to the retirements of recent carbon offsets. The CAR after retiring recent carbon offsets is 1.221% (statistically significant at the 5% level). In contrast, the response to the retirements of past carbon offsets is 0.972% and statistically insignificant at the 10% level. Recent offsets are considered higher quality as they are verified under the latest standards and methodologies. By retiring recent carbon offsets, firms send a more credible signal of their environmental commitment, which elicits a stronger reaction from investors. Our findings suggest that investors are discerning in their evaluation of carbon offsets, responding positively only to retirements of high-quality offsets.

To examine whether investors consider the quantity of retired offsets, Panel C compares carbon offset retirement dates based on the amount of offsets retired. Across the 236 retirement events, the quantity of retired carbon offsets varies widely. Using a median value of 1,062.5 units from our sample as the threshold, we compare the cumulative abnormal returns (CARs) surrounding above- and below-median retirement events. The results indicate that both above- and below-median offset retirements yield statistically insignificant CARs of 0.928% and 1.325%, respectively. The response to below-median offset retirements is even larger than that of above-median retirements, though neither is statistically significant. This suggests that investors prioritize the quality over the quantity of retired carbon offsets. Since investors are discerning, they may associate larger offset volumes with cheaper, lower-quality projects, which may send unreliable signals to the market. As a result, the responses of market to above- and below-median offset retirements are uniform.

To further support that investors pay attention to carbon offset retirements, in Panel D, we compare the cumulative abnormal return for first-time carbon offset retirements relative to seasoned retirements. Suppose the retirements attract investors' attention, the responses would be greater for the first-time retirements. Our results indicate that the CAR after first-time carbon offset retirement is 1.203% (statistically significant at the 10% level), which is larger than the CAR after seasoned retirement. Conversely, the response to the seasoned retirements is 0.748% and statistically insignificant at the 10% level. After the first-time retirement, investors have learned about the firms' commitment to the environment. As a result, the reaction to following retirement becomes less pronounced. This finding is consistent with Flammer (2021) who show that the market responds more strongly to the announcement of first-time green bond issuance.[12]

Put together, we find that investors care more about the quality of carbon offsets than the quantity. They react positively to high-quality carbon offset retirements, viewing them as credible signals of a company's environmental commitment. Conversely, large volumes of offsets may raise doubts about the reliability of the signals, especially if the offsets are linked to lower-quality, cheaper projects. This suggests that the benefits of greenwashing—such as using low-quality carbon offset projects to falsely claim environmental dedication—could be minimal. Given investors' focus on credible, high-quality offsets, firms attempting to greenwash would likely fail to gain significant investor support or the expected reputational rewards.[13]

4.3 Robustness

In this section, we conduct a series of robustness tests to address potential concerns and validate the reliability of our event study results. Table 4 summarizes these findings.

< Insert Table 4 here >

[12]Note that there is limited overlap among these characteristics, with the highest correlation—between "removal" and "recent"—being around -17%. This negative correlation helps rule out the possibility that our results are influenced by overlapping attributes. Other correlations are relatively weak, indicating minimal association among the other characteristics. The detailed correlation is reported in Table B.4.

[13]Here, we report our heterogeneity results by sub-samples. The limited number of retirement dates make it difficult to clearly identify cross-sectional differences.

We begin by outlining our approach to calculating abnormal returns. A key concern is the reliance on the market model, which may be influenced by additional priced factors during the sample period. To address this, we employ the global three-factor model developed by Fama et al. (1993), incorporating market, size (SMB), and book-to-market (HML) factors.[14] As shown in row 1 of Table 4, our findings remain robust under this alternative specification. To capture country-specific market dynamics not fully addressed by the global model, we then turn to country-specific stock market indices, such as the Nasdaq Composite Index for the U.S., the S&P ASX 200 Index for Australia, and the Nikkei 225 Index for Japan. These indices, sourced from Compustat Global and North America, serve as localized benchmarks. As indicated in row 2, the estimated CAR under this specification is 1.370% (statistically significant at the 5% level), further reinforcing the validity of our results. Additionally, we account for industry-specific trends by adjusting returns using industry benchmarks at the two-digit SIC level. This involves subtracting the average return of all stocks within the same country and industry on the same trading day.[15] As shown in row 3, the results remain robust, confirming that industry-wide effects do not drive our findings.

Next, we refine the methodology for calculating CARs and their standard errors. In the baseline approach, stocks are equally weighted when estimating average CARs. To address potential biases, we compute precision-weighted CARs, giving greater weight to stocks with lower return volatility. Row 4 shows that precision-weighted CARs remain positive and statistically significant, affirming the robustness of our findings. We also address temporal and cross-sectional correlations in returns by clustering standard errors at the firm level (row 5) and applying the "crude dependence adjustment" (CDA) method of Brown and Warner (1980) (row 6). Both approaches yield results consistent with the baseline, confirming the robustness of our estimates.

We then focus on the financial factors that may drive stock market reactions. One possible factor is government subsidies for carbon offset retirements. For instance, programs such as Australia's Emissions Reduction Fund (ERF) or tax incentives in South Africa, Colombia, and Sweden might incentivize firms to retire offsets for financial benefits rather than as a signal of environmental commitment. In this case, the observed stock market reaction could be attributed to the receipt of government subsidies. To address this concern, we exclude firms from these countries and rerun the event study. As shown in row 7, the estimated cumulative abnormal return (CAR) increases to 1.544% (statistically significant at the 5% level), indicating that our results are not driven by government subsidies.

[14]Data for these factors is sourced from Kenneth French's website at Dartmouth.

[15]Stocks with unique country and industry combinations are not adjusted due to the absence of comparable peers.

Another alternative hypothesis is that firms retire carbon credits as a result of strong financial performance. Under this scenario, the observed increase in stock prices could be attributed to the firm's overall good performance rather than the carbon offset retirement itself. To mitigate this concern, we exclude firms that announce financial results, such as equity or bond issuances or financial report releases, within the event window. Here, we manually review news surrounding each of the 236 retirement dates to identify and remove confounding events. This involves examining investor relations updates on firms' websites around the dates of carbon offset retirements. For example, The Walt Disney Company retired carbon offsets on February 1, 2021, but also released its first-quarter earnings for fiscal year 2021 on February 11, 2021.[16] Since the earnings release falls within the event window and could influence stock prices, we exclude this retirement from our analysis. In all, we remove 64 event dates with confounding events. After re-estimating CARs, the average increases to 1.732% (statistically significant at the 5% level), as shown in row 8, demonstrating that our results remain robust after controlling for these confounding factors.

In the next step, we assess the robustness of our event window. One concern is the potential for information leakage before the official retirement dates. In the baseline specification, we assume that all market reactions occur on or after the announcement date. To test this assumption, we extend the event window to include two trading days prior to the retirement date ([-2, 15]). As shown in row 9, the average CAR remains consistent with our baseline findings, suggesting that pre-release information does not materially affect our results. Furthermore, we address potential concerns regarding the choice of event window duration by examining both longer and shorter periods. Specifically, we consider a 21-day event window [0,20] and a shorter 8-day window [0,7], which is half of our benchmark setting. As shown in rows 10 and 11, the CARs remain positive and statistically significant, demonstrating the robustness of our event window.

Lastly, we address concerns about omitted retirement dates in our baseline sample. Of the 236 retirement dates analyzed, 10 were excluded because they did not fall on trading days. To evaluate the impact of this exclusion, we extend the sample to include these dates by replacing them with the nearest trading dates, yielding an expanded sample of 246 events. As shown in row 12, the CAR remains positive and statistically significant at the 5% level, affirming the robustness of our results. These robustness checks collectively validate the reliability and robustness of our event study findings.

[16] For more details, see "The Walt Disney Company Reports First Quarter Earnings for Fiscal 2021", February 2021.

5 Firms' Salience and Offset Retirements

To strengthen the evidence for our benchmark results, we turn to the transaction-level data on carbon offset retirements to further examine investors' preferences. This allows us to analyze how the salience of climate change influences firms' demand for carbon offsets. Additionally, unlike the retiree-by-date data used in the event study methodology, the transaction-level data captures the carbon offsets from different projects retired on the same date. Hence, we can further examine the heterogeneous impacts on firms' demand for various types of carbon offsets with this detailed data. Prior research (Pástor et al., 2021; Ardia et al., 2023) has shown that investors' preferences for "green" investments intensify as concerns about climate change grow. Consequently, firms are more likely to credibly signal their environmental commitment during periods of heightened awareness and concern about climate change. In essence, firms may anticipate greater investor willingness to pay and adjust their environmental practices accordingly to align with these preferences and maximize profitability.

Our previous analysis highlights that investors place significant value on the retirement of high-quality carbon offsets, such as removal offsets or those with recent vintage dates. In contrast, retiring larger volumes of offsets appears less effective in capturing investors' attention. If these preferences hold, we hypothesize that firms prioritize retiring high-quality carbon offsets, potentially at the expense of retiring smaller volumes, particularly during periods when climate concerns are more salient.

5.1 Effects of Temperature Anomalies on Offset Retirements

To test this hypothesis, we investigate the effect of temperature anomalies on carbon offset retirements. Temperature anomalies are used as a proxy for climate change concerns, as extreme weather conditions—whether unusually hot or cold—tend to heighten public awareness and concern about climate change (Herrnstadt and Muehlegger, 2014; Burke and Emerick, 2016; Choi et al., 2020). If investors prefer quality over quantity, firms would respond to these heightened concerns by retiring more high-quality carbon offsets during periods of extreme weather to align with investor preferences. Formally, we estimate the following baseline equation:

$$Y_{it} = \theta_0 + \theta_1 * Temp_{it} + \theta_2 * Temp_{it}^2 + \theta_3 * Prec_{it} + \theta_4 * Prec_{it}^2 + FE + Controls + \epsilon_{it} \quad (4)$$

where Y_{it} denotes the logarithm of the amount of retired carbon offsets for transaction i in year t. $Temp_{it}$ refers to temperature anomalies, while $Temp_{it}^2$ is the squared temperature anomalies to account for potential non-linear effects. Similarly, $Prec_{it}$ and $Prec_{it}^2$ represent precipitation anomalies and their squared terms, respectively. The model includes fixed effects (FE) for year, country, firm, and sector to control for specific characteristics that could otherwise bias the results. To ensure that the effects of temperature anomalies are driven by climate change concerns, we include a set of co-variates identified in the literature as being influenced by temperature. These include GDP per capita (e.g., Dell et al., 2012; Newell et al., 2021), urbanization (e.g., Marchiori et al., 2012; Cattaneo and Peri, 2016), climate change policies (e.g., Liao and Junco, 2022), and CO2 emissions per capita (Lehr and Rehdanz, 2024).[17]

Table 5 examines the relationship between temperature anomalies and carbon offset retirements for public firms from 2009 to 2022. Column (1) presents the baseline results without control variables, revealing a positive and significant coefficient for temperature anomalies (statistically significant at the 10% level) and a negative and significant coefficient for the squared temperature anomaly (also statistically significant at the 10% level). This inverted-U relationship indicates that firms reduce the volume of retired carbon offsets during extreme weather events. When control variables are added, as shown in Column (2), there remains weak evidence of an inverted-U relationship. The coefficient for temperature anomalies remains positive at 0.532 (statistically significant at the 5% level), while the squared term becomes statistically insignificant and negative at -0.476. These findings suggest that the demand for carbon offsets peaks at approximately 0.56-degree temperature anomalies, a value close to the average, and declines as temperature anomalies become more extreme.

< Insert Table 5 here >

Using temperature anomalies as a proxy for climate change concerns, the results suggest that investors do not prioritize the volume of retired carbon offsets. If they prefer quantity, firms would be expected to increase the volume of retirements in response to heightened climate concerns, leading to a U-shaped relationship between temperature anomalies and offset demand. However, our results indicate the opposite scenario, where firms reduce the volume of retired offsets when climate concerns are more salient. This finding is consistent with the event study results, which indicate that the stock market reaction is not influenced by the volume of offsets retired. Together, the evidence suggests that the quantity of offsets retired is not a credible signal of environmental commitment and does not capture investors' attention.

We then examine the heterogeneous effects of temperature anomaly by the quality of carbon offsets. As discussed before, companies would be more likely to retire high-quality carbon offsets during extreme weather if investors care about the quality of carbon

[17] Extreme temperature could affect output, rural-urban migration, CO2 emissions, and the possibility of implementing climate change policies. These co-variates might further influence the demand for carbon offsets. For example, output loss could reduce firms' demand for carbon offsets due to limited firms' revenue. Note that the variable ETS is omitted because of the collinearity with fixed effects.

offsets. Table 6 reports the heterogeneous effects by quality. Column (1) compares the effects on removal and reduction carbon offsets. We find that there is a U-shaped relationship between temperature anomaly and the amount of retired removal carbon offsets, suggesting that firms tend to retire more removal carbon offsets during extreme weather. In Column (2), we find a similar pattern when comparing the demand for recent and past carbon offsets. When it becomes extremely hot or cold, firms retire more recent carbon offsets relative to those with older vintage years.

< Insert Table 6 here >

These findings support the argument that investors prioritize the quality of carbon offsets over their quantity. During periods of extreme temperature, concerns about climate change become more pronounced, reflecting heightened awareness of environmental issues (Herrnstadt and Muehlegger, 2014; Burke and Emerick, 2016; Choi et al., 2020). Previous studies have shown that investors' preferences for sustainable actions intensify when climate change concerns rise, with a particular emphasis on firms demonstrating genuine environmental commitment (Pástor et al., 2021; Ardia et al., 2023). In line with these preferences, we find that firms strategically retire more high-quality carbon offsets during such periods, aligning their actions with investor expectations. Indeed, if investors were indifferent to the quality of carbon offsets, firms would have little incentive to alter their behavior during extreme temperature events. Thus, the observed increase in high-quality offset retirements during these periods underscores that investors view these offsets as meaningful signals of sustainability.

5.2 Robustness

In what follows, we evaluate the robustness and external validity of our findings on how temperature anomalies influence carbon offset retirements. One key concern relates to the accuracy of temperature data, particularly for developing countries, where sparse station coverage, measurement errors, and model constraints may compromise reliability. To address this, we re-estimate our regressions using an alternative dataset from the Climate Change Knowledge Portal. The results, presented in Tables B.5 and B.6, confirm that our findings remain robust across different temperature data sources.

Another factor to consider is the impact of carbon offset price fluctuations on demand, which could weaken the causal link between climate change concerns and offset retirements.[18] However, the lack of price data at the time of offset retirement prevents direct inclusion of this variable in our regressions. Additionally, as offsets are often held

[18]Price fluctuations are less likely to affect our event study, which uses retirement dates as shocks and examines stock market reactions to these events.

for several years before retirement, retirement-year prices may not reflect purchase-year prices. To mitigate this issue, we build on the approach of Trencher et al. (2024), incorporating carbon offset type-by-retirement year fixed effects to control for price variation across these dimensions. The results, presented in Table B.7, align with our baseline findings, indicating that price fluctuations do not drive our results.

Finally, we examine whether our findings extend beyond public firms. Signaling behaviors may also be relevant for other entities, such as private firms signaling environmental commitments to investors or governments signaling to attract environmentally conscious citizens. To test this, we expand our analysis to include all beneficiaries—governments, private firms, non-profits, and public firms. The results, presented in Tables B.8 and B.9, support the inverted-U relationship between temperature anomalies and overall carbon offset demand. Moreover, we find that during extreme temperature periods, beneficiaries exhibit stronger preferences for high-quality offsets, such as removal offsets or those with recent vintage years. These findings demonstrate that our results are consistent and robust across a broader sample.

6 A Simple Signaling Model

To illustrate the quality-quantity trade-off, we formalize our empirical findings on investor preferences and firm behavior through a simple signaling model. Our framework involves two key agents: a firm and a green investor. The firm can belong to one of two private types: green (genuinely committed to sustainability) or brown (primarily engaged in greenwashing). Green firms focus on substantive environmental initiatives aimed at achieving long-term impact, whereas brown firms prioritize symbolic actions with minimal effort toward genuine carbon reductions.

In each period, the firm first decides whether to participate in the voluntary carbon market. If the firm opts out, the period ends. Otherwise, it faces a trade-off between quality and quantity, as high-quality offsets, such as removal projects and newer offsets, are traded at higher prices. Specifically, the firm can choose to retire either a small number of high-quality offsets or a larger number of low-quality offsets within its budget constraints. The firm's choice of offsets acts as a signal, observable to the green investor. This signal shapes the investor's beliefs about the firm's type and, in turn, influences their investment decision.

6.1 Setup

Firm Types. Depending on its level of environmental commitment, the firm can be one of two types: green (G) or brown (B), represented as $T = \{G, B\}$. The firm's type reflects its environmental commitment and is private information known only to the firm. The green investor observes signals to infer this type. Nature assigns a type $t \in T$ for the firm, with probabilities $Pr(G) = q$ and $Pr(B) = 1 - q$. Thus, the green investor's prior belief that the firm is of type G is q.

Game Structure. The timing of decisions in each period is as follows:

1. The firm decides whether to participate in carbon offset retirements.

2. If the firm chooses not to participate, the period ends.

3. If the firm participates, it chooses to either retire high-quality carbon offsets or retire a large quantity of offsets, $m \in M = \{Quality, Quantity\}$.

4. The green investor observes m and updates the beliefs about the firm's type, $\mu(t|m)$.

5. Based on the updated belief, the green investor decides whether to invest in the firm, $a \in A = \{0, 1\}$ where $a = 1$ indicates an investment decision, and $a = 0$ indicates no investment.

Payoff for Investor. Our model focuses only on the behavior of green investors. Unlike traditional investors, who are solely concerned with financial performance, green investors assess firms based on their genuine commitment to environmental initiatives. This distinction enables us to isolate the interaction between green signaling and investor behavior.[19]

Green investors place a high value on sustainability and environmental responsibility. They derive positive utility $\kappa > 0$ from investing in green firms, negative utility $-\omega$ from investing in brown firms, and a normalized utility of 0 from not investing. Accordingly, the green investor's payoff function is as follows:

$$U_I(t, a) = \begin{cases} \kappa \text{ if } t = G, a = 1 \\ -\omega \text{ if } t = B, a = 1 \\ 0 \text{ if } a = 0 \end{cases} \tag{5}$$

Payoff for Firms. Next, we analyze the payoffs for firms, which arise from two

[19] Traditional investors, driven purely by financial returns, would remain indifferent to the quality or quantity of carbon offsets as long as the firm's total costs are the same. As their behavior does not influence the key mechanisms under study, we exclude them from the model to maintain analytical clarity.

primary sources: outsourcing benefits and reputation benefits. These components, as outlined in Kim et al. (2024), capture the key motivations for firms to retire carbon offsets.

Outsourcing benefits (ϕ_t) represent the cost savings and operational efficiencies achieved when a type-t firm substitutes carbon offsets for direct emissions reductions or innovations. By outsourcing emissions reductions to third-party offset providers, firms avoid the financial and logistical challenges of investing in on-site abatement technologies or process improvements. Since each carbon offset corresponds to one ton of emissions, these benefits scale with the quantity of offsets retired. For instance, brown firms, which prioritize symbolic actions over genuine sustainability, often maximize outsourcing benefits by retiring large volumes of low-cost offsets, aligning with their emphasis on symbolic rather than substantive carbon neutrality.

Reputation benefits (η_t), in contrast, stem from the ability of a firm of type t to credibly signal its commitment to sustainability. These benefits arise when investors interpret the firm's offset retirement as evidence of genuine environmental responsibility. High-quality offsets convey a stronger commitment to sustainability, as they often achieve direct emissions reductions, or deliver long-term ecological benefits. The extent of these benefits depends on investors' willingness to pay for green initiatives. Unlike outsourcing benefits, reputation benefits materialize only if investors respond positively to the firm's actions. If investors are indifferent or skeptical, these benefits fail to materialize.

The payoff function for a firm with type t where $t \in \{G, B\}$ is expressed as:

$$U_F(t, m, a(m)) = \begin{cases} \eta_t - c \text{ if } m = Quality, a = 1 \\ \rho_t - c \text{ if } m = Quantity, a = 1 \\ \phi_t - c \text{ if } m = Quantity, a = 0 \\ -c \text{ if } m = Quality, a = 0 \\ 0 \text{ if no participation} \end{cases} \tag{6}$$

Here, the firm's payoff function, $U_F(t, m, a(m))$, represents the utility derived from its strategic decisions in the carbon offset market, which depends on three key factors: the firm's type is green ($t = G$) or brown ($t = B$), the firm's choice between offset quality ($m =$ Quality) and quantity ($m =$ Quantity), and the investor's decision to invest ($a = 1$) or not ($a = 0$). Additionally, if the firm chooses to retire carbon offsets, it incurs a fixed cost, c.

When the firm selects high-quality offsets and secures investment ($m =$ Quality, $a = 1$), it earns a reputation benefit η_t, reduced by the fixed cost c. Alternatively, if the firm prioritizes quantity and attracts investment ($m =$ Quantity, $a = 1$), it receives a combined payoff of outsourcing and reputation benefits, ρ_t, also reduced by c. On the other hand, retiring low-quality offsets without attracting investment (m = Quantity, $a = 0$) yields only the outsourcing benefit ϕ_t, minus c. For high-quality offsets without investor support (m = Quality, $a = 0$), the firm incurs a net loss equal to c. Finally, if the firm chooses its outside option and refrains from engaging in offset activity, its utility is normalized to zero.

Assumptions. To ensure that the model accurately reflects the empirical context, we impose the following assumptions on the parameters.

1. $\kappa q - w(1-q) = 0$
2. $\eta_G \geq \phi_G$, $\eta_B \leq \phi_B$
3. $\eta_G \geq c$, $\phi_B \geq c$
4. $\rho_G < 0 < \rho_B$
5. η_t increases with climate change concerns, where $t \in \{G, B\}$

Assumption 1 ensures that the prior expected utility from investing is equal to the utility of not investing. Put differently, investors are indifferent between investing and not investing before receiving signals (e.g., carbon offset retirements).

Building on this, Assumptions 2 and 3 impose conditions on the utility parameters of firms to capture the trade-offs they face. Specifically, green firms prioritize long-term sustainability goals and are more inclined to pursue reputation benefits ($\eta_G \geq \phi_G$), while brown firms, motivated by cost efficiency and symbolic compliance, tend to favor outsourcing benefits ($\eta_B \leq \phi_B$). These assumptions underscore the signaling mechanism that shapes investor perceptions and decisions in the voluntary carbon market. Furthermore, for both green and brown firms, the reputation or outsourcing benefits must exceed the cost of retiring carbon offsets ($\eta_G \geq c$ and $\phi_B \geq c$), ensuring that participation in the market remains rational.

Assumption 4 addresses the unique challenges faced by green firms. While symbolic actions like retiring large volumes of offsets might attract investment, they also expose green firms to reputational risks, such as accusations of greenwashing (Walker and Wan, 2012). These risks may outweigh the financial gains from such investments, leading to a negative net payoff for green firms engaging in these actions ($\rho_G < 0$).[20] Conversely, brown firms derive positive payoffs ($\rho_B > 0$) are less concerned with reputational risks and primarily focus on cost efficiency and attracting investment through high-volume

[20] Here, the zero has no economic significance. The negative ρ_G indicates that retiring high-quality offsets without investment is better than retiring large volumes of offsets, even when accompanied by investment.

offset retirements. For brown firms, symbolic compliance often aligns with their goals, allowing them to benefit financially without the same level of scrutiny faced by green firms. Assumption 4 thus highlights how reputational considerations disproportionately impact green firms, shaping their strategic choices within the voluntary carbon market.

Lastly, Assumption 5 reflects the anticipation that rising climate change concerns will increase investor willingness to pay for carbon offsets (Pástor et al., 2021). This aligns with evidence showing that heightened awareness of environmental issues strengthens the market demand for sustainable practices, enhancing the attractiveness of carbon offsets as an investment.

Strategies. We solve this signaling game by focusing on Perfect Bayesian Equilibrium (PBE), which requires sequential rationality and that beliefs are updated consistently with Bayes' rule whenever possible. Upon receiving each signal m, the green investor selects the optimal action $a^*(m)$ to maximize utility based on their updated beliefs:

$$a^*(m) = arg\max_{a\in A}\sum_{t\in T} U_I\left(t,a\right)\mu\left(t|m\right) \tag{7}$$

For $t \in \{G, B\}$, the firm's message $m^*(t)$ must be optimal given the investor's strategy $a^*(.)$. That is:

$$m^*(t) = arg\max_{m\in M} U_F\left(t,m,a^*(m)\right) \tag{8}$$

For each received m, if there exists t such $m^*(t) = m$, then the investor's belief at the information set corresponding to m must follow from Bayes' rule and firm's strategy $m^*(.)$:

$$\mu\left(t|m\right) = \frac{Pr\left(t\right)}{\sum_{t'\in T \text{ where } m^*(t')=m} Pr\left(t'\right)} \tag{9}$$

6.2 Analysis

Our signaling model provides the following propositions regarding investors' preferences and firms' demand for carbon offsets:

Proposition 1. *In the unique Perfect Bayesian Equilibrium (PBE) that satisfies the intuitive criterion, the green firm retires high-quality carbon offsets, while the brown firm retires a large quantity of carbon offsets. The green investor chooses to invest only upon observing high-quality retirements, forming posterior beliefs* $\mu(G|Quality) = 1$ *and* $\mu(B|Quantity) = 1$.

The proof is provided in Appendix A.1. In equilibrium, $\mu(G|Quality) = 1$ indicates that the green investor views high-quality offset retirements as credible signals of genuine environmental commitment. Consequently, the investor is more likely to allocate funds to firms that retire high-quality offsets, resulting in a positive effect on their stock prices. These theoretical results align with our empirical findings, which show that firms experience stock price gains after retiring removal offsets or offsets with recent vintages. In contrast, the belief $\mu(B|Quantity) = 1$ reflects the green investor's interpretation of large volumes of low-quality offsets as indicative of greenwashing. As a result, the investor refrains from investing in firms signaling through low-quality retirements, consistent with empirical evidence that shows no significant stock price impact from the quantity of offsets retired.

Given these investor beliefs, the green firm, which places a higher value on reputation benefits, opts to retire high-quality carbon offsets to signal its commitment credibly. On the other hand, the brown firm, driven by outsourcing benefits rather than reputation, retires larger volumes of low-quality offsets. This separating equilibrium mirrors the observed empirical trends in the voluntary carbon market (VCM), where offset quality is a distinguishing factor between firm types. Since low-quality offsets dominate the market in volume, the proportion of high-quality offset retirements remains persistently low across countries and over time.

Proposition 2. *When climate change concerns become more salient, a pooling equilibrium may emerge in which both types of firms retire high-quality carbon offsets, provided that the reputation benefits for the brown firm exceed its outsourcing benefits. In this pooling equilibrium, the demand for high-quality carbon offsets increases, while the overall quantity of retired offsets decreases.*

The proof is detailed in Appendix A.2. This proposition employs a standard comparative static approach to examine firms' strategic responses to heightened climate change concerns. As these concerns grow, firms anticipate greater reputation benefits due to the investor's increased willingness to pay for green assets. In response, the green firm continues to retire high-quality carbon offsets to align with investor preferences. Similarly, if the reputation benefits for the brown firm surpass its outsourcing benefits, it may also transition to retiring high-quality offsets. This strategic shift from focusing on "quantity" to prioritizing "quality" reduces the total volume of retired offsets while increasing the demand for high-quality offsets. However, as both firm types adopt the same signal (retiring high-quality offsets), the signal loses its ability to differentiate between them. Consequently, the signal becomes uninformative, and the green investor bases their decision on prior beliefs, investing with a probability of $\mu(G|Quality) = q$, equal to their initial expectation.

Our empirical evidence aligns closely with this proposition. Using temperature as a proxy for heightened climate change concerns, we observe that during periods of extreme temperatures, firms increasingly prioritize retiring high-quality carbon offsets to meet rising investor demand for credible environmental actions. Concurrently, the total volume of retired offsets decreases, signaling a strategic shift from quantity to quality. This behavioral adjustment underscores the trade-off firms navigate between signaling environmental credibility to enhance reputation benefits and managing the associated costs, reflecting the theoretical dynamics outlined in the model.

There are clear distinctions in how investors perceive and respond to sustainability efforts. Our findings underscore the critical role of high-quality carbon offsets in signaling credible environmental commitment to investors. Retiring such offsets aligns with investor preferences, as they are well-informed and discerning in the voluntary carbon market. In contrast, greenwashing strategies, such as overstating mitigation efforts with low-quality offsets, fail to capture meaningful investor support. Firms that invest in costly, high-quality offsets gain both investor trust and reputational benefits, while low-quality offsets offer limited market advantages. This highlights the importance of genuine sustainability efforts for firms aiming to secure investor confidence and achieve competitive success.

7 Conclusion

In this paper, we highlight investors' preferences for carbon offsets, a novel tool in sustainable finance. The heterogeneity in the quality, certification, and environmental impact of offsets makes credibility a key factor in their valuation. We show that investors demonstrate a sophisticated understanding of the voluntary carbon market, distinguishing between high- and low-quality offsets and consistently prioritizing quality over quantity. Specifically, investors view high-quality carbon offset retirements as strong signals of a firm's reputation and environmental commitment. These preferences underscore the importance of aligning carbon offset strategies with market expectations to enhance environmental credibility and build investor trust.

By analyzing stock market reactions to the retirement of carbon offsets, we find a cumulative abnormal return (CAR) of 1.126% over the 15 trading days following the retirement. The positive market response is driven primarily by high-quality carbon offsets, such as removal offsets and those with recent vintage years. In contrast, changes in the quantity of offsets retired do not have a statistically significant impact on returns. This preference for quality over quantity are further supported by firms' demand for carbon offsets. As climate change concerns become more salient with extreme temperatures, firms respond by increasing their retirement of high-quality carbon offsets. However, the total volume of retired offsets decreases. A simple signaling model explains these findings, demonstrating that green investors prioritize the quality of carbon offsets as a credible indicator of a firm's environmental commitment.

These insights underscore the critical role of voluntary carbon markets in enabling firms to effectively signal environmental responsibility. However, to fully unlock this potential, robust governance frameworks are essential. Policymakers can play a pivotal role by establishing enforceable guidelines to define and standardize carbon offset quality, ensuring offsets adhere to high environmental and ethical standards. Equally important is transparency; requiring detailed public disclosure of offset retirements will enhance investor trust and facilitate meaningful cross-industry comparisons. By aligning carbon offset practices with investor expectations and market demands, voluntary carbon markets can not only drive meaningful climate action but also embed sustainability into corporate strategies and goals.

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Tables and Figures

Table 1: Summary Statistics at Transaction Level

	Obs.	Mean	St.Dev.	Min.	Max.
	(1)	(2)	(3)	(4)	(5)
Panel A: Carbon Offset					
Carbon Offset Amount	2,810	19,675	63,725	1	1,190,923
Vintage Duration	2,810	435	362	10	3,102
Verification Duration	2,810	1,079	909	-2,417	5,497
Trading Duration	2,810	553	568	0	4,625
Removal Carbon Offset	2,810	.24	.43	0	1
Recent Carbon Offset	2,810	.60	.49	0	1
Domestic Carbon Offset	2,810	.04	.18	0	1
Panel B: Country-by-year					
Temperature Anomaly	2,810	.510	.437	-.767	1.656
Rainfall Anomaly	2,810	17.449	87.464	-213.423	488.231
GDP per capita	2,810	46,578.69	10,773.39	7,315.122	88,366.22
Urbanization	2,810	83.666	8.515	18.651	100
CO2 per capita	2,810	10.839	4.615	.924	18.252
ETS	2,810	.764	.425	0	1
Carbon Tax	2,810	.267	.443	0	1

Notes: This table reports the mean, standard deviation, minimum, and maximum based on the carbon offset retirement by public firms from 2009 to 2022 at transaction level. Vintage duration is the gap between vintage start and end dates. Verification duration refers to the periods between vintage end and issuance dates. Trade Duration is the gap between offset issuance date and the retirement date. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. We consider carbon offsets be recent if the gap between retirement date and vintage start date is less than or equal to its median value, which is 5 years. Carbon offsets are labeled as domestic offsets if they are generated from domestic emissions reduction or removal project. Temperature and rainfall anomaly is calculated by the deviation from its long-run mean (1991-2020). Urbanization is measured by the percentage of urban residents. Dummy variable ETS and Carbon Tax are indicators for countries that have implemented ETS and carbon tax policy respectively.

Table 2: Stock Market Reaction to Carbon Offset Retirement

Event time	CAR	Std. err.
[-20,-11]	0.452	0.406
$[-10,-1]$	-0.427	0.475
$[0,15]$	1.126**	0.560
$[16,30]$	-0.149	0.568
$[31,60]$	0.582	0.817

Notes: This table reports the average cumulative abnormal return (CAR) for different time windows around the retirement of carbon offset. The sample consists of N= 236 carbon offset retirement event dates. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Table 3: Cross-sectional Heterogeneity

	CAR	Std. err.
Panel A: Removal vs. Reduction		
Removal offsets (N=55)	1.941**	0.896
Reduction offsets (N=181)	0.879	0.677
Panel B: Recent vs. Past		
Offsets with recent vintage (N=146)	1.221**	0.611
Offsets with past vintage (N=90)	0.972	1.087
Panel C: Above- vs. Below-median		
Offset amount above-median (N=118)	0.928	0.687
Offset amount below-median (N=118)	1.325	0.886
Panel D: First-time vs. Seasoned		
First-time carbon offset retirement (N=196)	1.203*	0.636
Seasoned carbon offset retirement (N=40)	0.748	1.097

Notes: This table reports the average CAR[0, 15] for different sub-samples. Panel A distinguishes between removal carbon offsets and reduction carbon offsets. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. Panel B distinguishes between carbon offsets with recent and past vintage years. We consider carbon offsets be recent if the gap between retirement and vintage start date is less than or equal to its median value, which is 5 years. Panel C distinguishes between above- versus below-median amount of carbon offset retirement. Panel D compares first-time with seasoned retirements of carbon offsets. *, **, and *** denotes significance at the 10%, 5%, and 1% level, respectively.

Table 4: Robustness

	CAR	Std. err.
1. Global three-factor model of Fama and French	0.983*	0.562
2. Country-specific market indices	1.370**	0.549
3. Industry-adjusted CARs	0.824*	0.499
4. Precision-weighted CARs	0.890*	0.455
5. Clustered standard error at firm level	1.126**	0.542
6. Cross-sectional correlation	1.126*	0.599
7. Excluding countries with offset retirement subsidies	1.544**	0.627
8. Excluding confounding events	1.732**	0.683
9. Accounting for pre-release information	1.224**	0.589
10. Event window with longer periods	1.350**	0.597
11. Event window with shorter periods	0.696*	0.383
12. Including events not on trading days	1.121**	0.539

Notes: This table reports alternative ways of computing CAR[0, 15]. In row 1, the global three-factor model of Fama et al. (1993) is used instead of the market model. In row 2, country-specific market indices is used in lieu of the MSCI All Country World Equity Index. In row 3, returns are industry adjusted by subtracting the average return across all stocks in our sample on a given trading day in the same country and same two-digit SIC industry. Row 4 reports the precision-weighted average CAR. Row 5 reports the standard error clustered at the firm level. In row 6, standard errors are computed using the "crude dependence adjustment" (CDA) of Brown and Warner (1980). Row 7 excludes beneficiaries from countries that provide subsidies for retiring carbon offsets (Australia, South Africa, Columbia, and Sweden). Row 8 excludes the event dates if there are any confounding events from that day to the following 15 trading days (the event window), such as the announcement of equity issues, bond issues, or quarterly earnings. In row 9, we account for the possibility of pre-release information on carbon offset retirement by including 2 trading days prior to the retirements. Row 10 and 11 use event windows with longer ([0, 20]) and shorter periods ([0, 7]), respectively. In row 12, we include the event dates those are not on trading days by using the nearest trading dates. The new sample size is 246 dates. *, **, and *** denotes significance at the 10%, 5%, and 1% level, respectively.

Table 5: Effect of Extreme Temperature on Carbon Offset Demand

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	0.598*	0.532**
	(0.306)	(0.253)
Temp. Anomaly sq.	-0.479*	-0.476
	(0.272)	(0.284)
Precipitation Anomaly	-0.00364**	-0.00449***
	(0.00137)	(0.00144)
Precipitation Anomaly sq.	1.90e-05**	1.75e-05*
	(7.34e-06)	(9.82e-06)
GDP per capita		-15.61***
		(4.783)
Urbanization		-1.435***
		(0.496)
Carbon Tax		0.137
		(1.203)
Emissions per capita		0.521**
		(0.201)
Constant	7.161***	289.4***
	(0.123)	(50.01)
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	2,677	2,677
R-squared	0.559	0.567

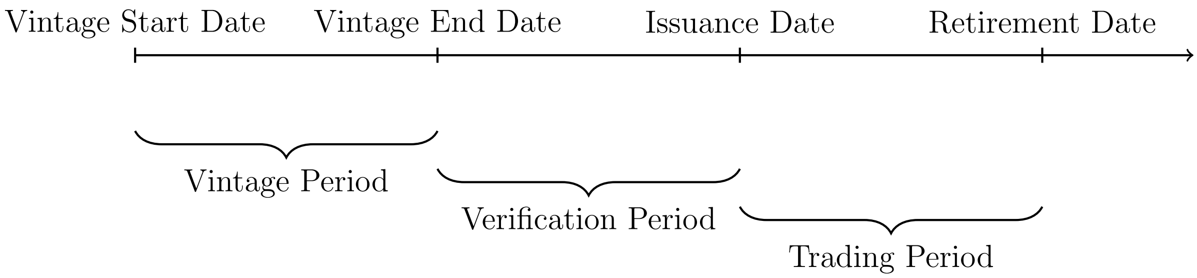
Notes: Based on the carbon offset retirement records of public firms over the world from 2009 to 2022, this table reports the impact of temperature anomaly on the demand carbon offsets. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Temperature anomaly is calculated by the deviation from the 1991–2020 mean. GDP per capita, urbanization, precipitation anomaly, indicator for carbon tax, and CO2 emission per capita are included as control variables. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Table 6: Heterogeneous Effects on Carbon Offset Demand by Quality

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	1.145***	0.716**
	(0.225)	(0.301)
Temp. Anomaly sq.	-1.086***	-0.883***
	(0.303)	(0.304)
Temp. Anomaly $\times \mathbb{1}$(Removal)	-2.768***	
	(0.869)	
Temp. Anomaly sq. $\times \mathbb{1}$(Removal)	2.472**	
	(0.974)	
Temp. Anomaly $\times \mathbb{1}$(Recent)		-0.224
		(0.275)
Temp. Anomaly sq. $\times \mathbb{1}$(Recent)		0.682**
		(0.316)
Control Variables	Y	Y
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	2,677	2,677
R-squared	0.573	0.569

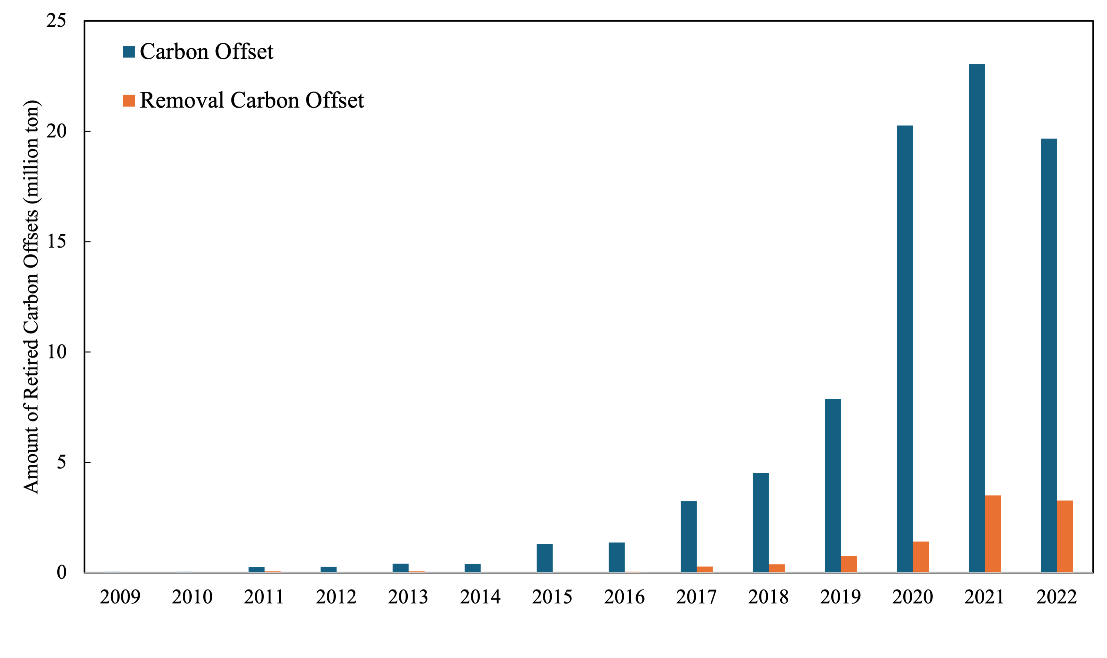
Notes: This table reports the heterogeneous effect of temperature anomaly on the demand for carbon offsets by quality. In column (1), we group carbon offsets into reduction offsets and removal offsets. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. In column (2), we group carbon offsets by the gap between retirement date and vintage start date. We consider carbon offsets be recent if the gap is less than or equal to its median value, which is 5 years. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Temperature anomaly is calculated by the deviation from the 1991–2020 mean. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Figure 1: Timeline for Carbon Offset Transactions



Notes: This figure presents the timeline for carbon offset transactions, with four key events—vintage start, vintage end, issuance, and retirement—plotted above the horizontal arrow. The period between the vintage start and end represents the vintage duration, while the gap between the vintage end and issuance date is the verification duration. Finally, the trading duration is the time between the issuance and retirement dates.

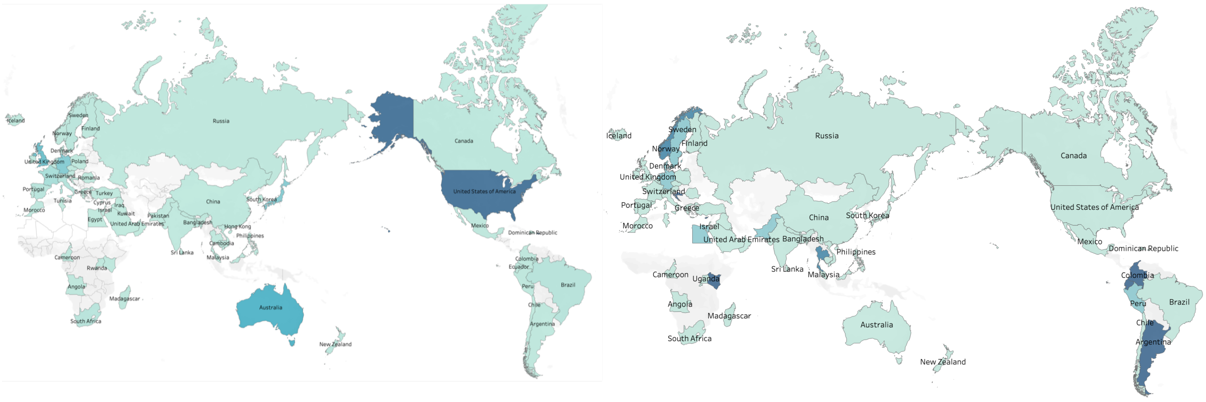
Figure 2: Carbon Offset Retirements over Time



Notes: This figure reports the amount of total retired carbon offsets (in ton) and total retired removal carbon offsets on an annual basis, using all beneficiaries from 2009–2022. The blue and orange bars refer to the total amount of retired carbon offsets and the amount of retired removal carbon offsets across different years, respectively.

Figure 3: Carbon Offset Retirements across Countries

(a) Amount of Carbon Offsets (b) Share of Removal Offsets



Notes: This figure plots the amount of total retired carbon offsets in Panel (a) as well as the share of retired removal offsets by country in Panel (b), using all beneficiaries from 2009–2022. The share of retired removal carbon offsets is calculated by the total amount of retired removal carbon offsets divided by the total amount of retired carbon offsets. The color gets darker if the amount of retired carbon offsets or the share of retired removal carbon offsets is larger in a certain country.

Online Appendix

Do Investors Care about Carbon Offsets?

A Theory Appendix

A.1 Proof of Proposition 1

Proof. When the firm retires high-quality carbon offsets, the investor decides whether to invest based on his expected utility. Since we normalize the utility of not investing at 0, the expected utility of not investing is always 0. Hence, the investor would choose to invest iff:

$$U_I(G,1)\mu(G|Quality) + U_I(B,1)\mu(B|Quality) \geq 0$$

The condition can be rewritten as $\kappa\mu(G|Quality) \geq \omega\mu(B|Quality)$. Since we assume that $\kappa q - w(1-q) = 0$, implying that the investor will invest if and only if $\mu(G|Quality) \geq q$ and $\mu(B|Quality) \leq 1-q$.

Given the payoff function of the firm, the best responses of the green and brown firm are to retire high-quality carbon offsets $m^*(G) = Quality$ and to retire a large quantity of carbon offsets $m^*(B) = Quantity$. The optimal payoffs for the green and brown firms are $\eta_G - c$ and $\phi_B - c$. Since we assume that $\eta_G \geq c$ and $\phi_B \geq c$, the optimal payoffs for the green and brown firms are positive, suggesting that the brown firm would engage in voluntary carbon market with a large quantity of retired carbon offsets. In contrast, the green firm focuses on retiring high-quality carbon offsets. The beliefs of the investor at the equilibrium are $\mu(G|Quality) = 1 > q$ and $\mu(G|Quantity) = 0 < 1-q$. This PBE satisfies intuitive criterion. For $m(G) = Quantity$, which is off the equilibrium path and is equilibrium-denominated for the green firm, we have $\mu(G|Quantity) = 0$. Similar for $m(B) = Quality$, we have $\mu(B|Quality) = 0$.

In contrast, when the firm retires a large amount of carbon offsets, the investor would invest iff:

$$U_I(G,1)\mu(G|Quantity) + U_I(B,1)\mu(B|Quantity) \geq 0$$

This can be written as $\kappa\mu(G|Quantity) \geq \omega\mu(B|Quantity)$. So, the condition for the investor to invest in this case is that $\mu(G|Quantity) \geq q$. Given the payoff function of the firm, since $\rho_G < 0$, the utility of retiring high-quality carbon offsets is higher. Thus, the green firm has incentives to deviate from the quantity to the quality. Accordingly, the belief $\mu(G|Quantity) \geq q$ fails intuitive criterion.

A.2 Proof of Proposition 2

Proof. The proof of this proposition is intuitive. When the climate change concerns become more salient, the firm expects high utility $\eta'_G \geq \eta_G$ and $\eta'_B \geq \eta_B$. Hence, the green firm would have large payoff by retiring high-quality carbon offsets, while the brown firm would choose to retire high-quality carbon offsets if and only if $\eta'_B \geq \phi_B$. If the brown firm decides to switch from quantity to high-quality carbon offsets, the overall quantity of retired carbon offsets decreases. However, the demand for high-quality carbon offsets increases when climate change concerns become more salient. In this equilibrium, the signal becomes uninformative, as both the green and brown firms retire high-quality carbon offsets. Therefore, the posterior beliefs of the investor are identical to the prior beliefs, with $\mu(G|Quality) = Pr(G) = q$ and $\mu(B|Quality) = Pr(B) = 1 - q$.

B Empirical Appendix

B.1 Additional Tables and Graphs

Table B.1: Additional Summary Statistics for All Beneficiaries

	Obs.	Mean	St.Dev.	Min.	Max.
	(1)	(2)	(3)	(4)	(5)
Carbon Offset Variables					
Carbon Offset Amount	8,709	9,503	40,484	1	1,190,923
Vintage Duration	8,709	407	301	10	3,651
Verification Duration	8,709	1,049	913	-2,417	5,497
Trading Duration	8,709	640	675	0	4,625
Removal Carbon Offset	8,709	.18	.38	0	1
Recent Carbon Offset	8,709	.62	.49	0	1
Domestic Carbon Offset	8,709	.05	.22	0	1
Country-by-year Variables					
Temperature Anomaly	8,709	.489	.484	-1.465	1.795
Rainfall Anomaly	8,709	-5.735	86.402	-616.077	488.231
GDP per capita	8,709	44,902.826	12,239.91	1,343.444	88,366.219
Urbanization	8,709	82.569	11.306	16.47	100
CO2 per capita	8,709	10.072	4.973	.103	26.053
ETS	8,709	.73	.444	0	1
Carbon Tax	8,709	.288	.453	0	1

Notes: This table reports the mean, standard deviation, minimum, and maximum based on the carbon offset retirement from 2009 to 2022 at transaction level. Vintage duration is the gap between vintage start and end dates. Verification duration refers to the periods between vintage end and issuance dates. Trade Duration is the gap between offset issuance date and the retirement date. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. We consider carbon offsets be recent if the gap between retirement date and vintage start date is less than or equal to its median value, which is 5 years. Carbon offsets are labeled as domestic offsets if they are generated from domestic emissions reduction or removal project. Temperature and rainfall anomaly is calculated by the deviation from its long-run mean (1991-2020). Urbanization is measured by the percentage of urban residents. Dummy variable ETS and Carbon Tax are indicators for countries that have implemented ETS and carbon tax policy respectively.

Table B.2: Carbon Offset Retirement over Time

Year	Total Offset Amount	Removal Amount	Removal Share
2009	47,089	0	0
2010	54,815	11,000	0.201
2011	252,582	61,503	0.243
2012	273,342	25,000	0.091
2013	416,364	67,867	0.163
2014	402,044	0	0
2015	1,300,146	23,603	0.018
2016	1,377,761	52,936	0.038
2017	3,246,894	278,745	0.086
2018	4,525,168	385,121	0.085
2019	7,885,115	764,849	0.097
2020	20,267,870	1,419,764	0.070
2021	23,047,682	3,505,454	0.152
2022	19,664,290	3,279,127	0.167

Notes: This table reports the amount of total retired carbon offset (in ton), total retired removal carbon offsets as well as the share of retired removal offset on an annual basis, using all beneficiaries from 2009–2022.

Table B.3: Carbon Offset Retirement by Country

Country	Total Offset Amount	Removal Amount	Removal Share
United States	28,932,128	4,429,060	.153
Australia	14,355,851	282,954	.02
United Kingdom	11,041,605	1,888,838	.171
Germany	7,832,055	1,717,595	.219
Japan	7,561,531	103,593	.014
France	2,937,011	378,916	.129
Italy	1,386,421	7,376	.005
Netherlands	1,261,617	295,548	.234
Brazil	1,159,413	24,445	.021
Switzerland	1,007,676	123,548	.123
South Africa	979,344	85,050	.087
Spain	946,820	42,672	.045
Sweden	692,704	140,569	.203
Canada	534,722	77,867	.146
New Zealand	470,260	44,083	.094
Morocco	348,853	50,020	.143
Austria	263,430	9,923	.038
Finland	202,120	20,475	.101
Luxembourg	145,034	0	0
China	116,852	2,748	.024
India	82,355	2,645	.032
Denmark	82,292	25,046	.304
Egypt	78,256	23,256	.297
Mauritius	53,816	0	0
Norway	42,371	30,320	.716
Others	246,624	68,422	.277

Notes: This table reports the amount of total retired carbon offset (in ton), total retired removal carbon offsets as well as the share of retired removal offset by country, using all beneficiaries from 2009–2022. The share of retired removal carbon offsets is calculated by the total amount of retired removal carbon offsets divided by the total amount of retired carbon offsets.

Table B.4: Correlation Matrix

	Removal	Recent	Above-median	First-time
Removal	1.0000			
Recent	-0.1656	1.0000		
Above-median	0.1241	0.0196	1.0000	
First-time	-0.0181	-0.0059	0.0241	1.0000

Notes: This table reports the correlation between four carbon offset characteristics: indicator for removal, recent, above-median, and first-time. The diagonal values are all 1.0000, representing each variable's perfect correlation with itself. Off-diagonal values show the pairwise correlations between variables, with positive values indicating a direct relationship and negative values indicating an inverse relationship.

Table B.5: Robustness – Alternative Data on Temperature

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	0.715**	0.647*
	(0.343)	(0.355)
Temp. Anomaly sq.	-0.662	-0.626
	(0.388)	(0.407)
Precipitation Anomaly	-0.00394***	-0.00465***
	(0.00125)	(0.00133)
Precipitation Anomaly sq.	2.14e-05***	1.92e-05*
	(7.65e-06)	(9.58e-06)
GDP per capita		-15.64***
		(4.869)
Urbanization		-1.411***
		(0.492)
Carbon Tax		0.180
		(1.186)
Emissions per capita		0.535***
		(0.184)
Constant	7.161***	287.6***
	(0.108)	(49.10)
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	2,677	2,677
R-squared	0.559	0.567

Notes: This table reports the robustness for the effect of temperature on carbon offset demand, based on the temperature data from Climate Change Knowledge Portal, World Bank. Temperature and rainfall anomaly is calculated by the deviation from its long-run mean (1991-2020). The dependent variable is carbon offset retirement amount. The amounts are reported in their logarithm values. GDP per capita, urbanization, precipitation anomaly, indicator for carbon tax, and CO2 emission per capita serve as control variables. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Table B.6: Robustness - Alternative Data on Temperature by Quality

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	1.471***	0.911*
	(0.383)	(0.508)
Temp. Anomaly sq.	-1.418***	-1.077**
	(0.400)	(0.478)
Temp. Anomaly $\times\mathbb{1}$(Removal)	-3.020***	
	(0.791)	
Temp. Anomaly sq. $\times\mathbb{1}$(Removal)	2.741***	
	(0.852)	
Temp. Anomaly $\times\mathbb{1}$(Recent)		-0.332
		(0.460)
Temp. Anomaly sq. $\times\mathbb{1}$(Recent)		0.750*
		(0.439)
Control Variables	Y	Y
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	2,677	2,677
R-squared	0.574	0.569

Notes: This table reports the robustness for the heterogeneous effects by the quality of carbon offsets, based on the temperature data from Climate Change Knowledge Portal, World Bank. Temperature and rainfall anomaly is calculated by the deviation from its long-run mean (1991-2020). In column (1), we group carbon offsets into reduction offsets and removal offsets. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. In column (2), we group carbon offsets by the gap between retirement date and vintage start date. We consider carbon offsets be recent if the gap is less than or equal to its median value, which is 5 years. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Table B.7: Robustness – Price Effects

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	0.930***	0.909**
	(0.303)	(0.337)
Temp. Anomaly sq.	-0.894***	-1.014**
	(0.302)	(0.402)
Temp. Anomaly $\times\mathbb{1}$(Removal)	-2.615***	
	(0.426)	
Temp. Anomaly sq. $\times\mathbb{1}$(Removal)	2.401***	
	(0.673)	
Temp. Anomaly $\times\mathbb{1}$(Recent)		-0.581*
		(0.324)
Temp. Anomaly sq. $\times\mathbb{1}$(Recent)		0.906**
		(0.427)
Control Variables	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Type-by-year Fixed Effects	Y	Y
Observations	2,643	2,643
R-squared	0.625	0.622

Notes: This table rules out the effects of carbon offset price fluctuation on carbon offset demand by including type-by-year fixed effects. In column (1), we group carbon offsets into reduction offsets and removal offsets. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. In column (2), we group carbon offsets by the gap between retirement date and vintage start date. We consider carbon offsets be recent if the gap is less than its median value, which is 5 years. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Temperature anomaly is calculated by the deviation from its long-run mean. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Table B.8: Robustness – Full Sample with All Retirement Beneficiaries

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	0.559***	0.543***
	(0.200)	(0.152)
Temp. Anomaly sq.	-0.402***	-0.366***
	(0.128)	(0.128)
Precipitation Anomaly	-0.000639	-0.000783
	(0.000846)	(0.000827)
Precipitation Anomaly sq.	1.33e-06	-1.45e-07
	(4.14e-06)	(4.69e-06)
GDP per capita		-2.666
		(3.076)
Urbanization		-0.597**
		(0.284)
Carbon Tax		-0.0594
		(0.462)
Emissions per capita		0.425***
		(0.107)
Constant	6.056***	79.60*
	(0.0732)	(46.27)
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	7,817	7,817
R-squared	0.674	0.676

Notes: Based on the carbon offset retirement records of all beneficiaries over the world, this table reports the impact of temperature anomaly on the demand carbon offsets. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Temperature anomaly is calculated by the deviation from its long-run mean. GDP per capita, urbanization, precipitation anomaly, indicator for carbon tax, and CO2 emission per capita are included as control variables. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.

Table B.9: Robustness – Full Sample with All Retirement Beneficiaries by Quality

Dep. Var.:	Log(Offset Demand)	Log(Offset Demand)
	(1)	(2)
Temp. Anomaly	0.627***	0.905***
	(0.149)	(0.206)
Temp. Anomaly sq.	-0.435***	-0.844***
	(0.133)	(0.224)
Temp. Anomaly $\times \mathbb{1}$(Removal)	-0.795**	
	(0.367)	
Temp. Anomaly sq. $\times \mathbb{1}$(Removal)	0.464*	
	(0.246)	
Temp. Anomaly $\times \mathbb{1}$(Recent)		-0.435
		(0.341)
Temp. Anomaly sq. $\times \mathbb{1}$(Recent)		0.718**
		(0.348)
Control Variables	Y	Y
Year Fixed Effects	Y	Y
Country Fixed Effects	Y	Y
Firm Fixed Effects	Y	Y
Sector Fixed Effects	Y	Y
Observations	7,817	7,817
R-squared	0.677	0.677

Notes: Based on the carbon offset retirement records of all beneficiaries over the world, this table reports the heterogeneous effect of temperature anomaly on the demand for carbon offsets by quality. In column (1), we group carbon offsets into reduction offsets and removal offsets. Removal carbon offsets are those generated from removal projects, as categorized by the Voluntary Registry Offsets Database. In column (2), we group carbon offsets by the gap between retirement date and vintage start date. We consider carbon offsets be recent if the gap is less than its median value, which is 5 years. The dependent variables denote the amount of carbon offset retirement. The amounts are reported in their logarithm values. Temperature anomaly is calculated by the deviation from its long-run mean. Clustering is done at the country level. The robust standard errors are reported in parenthesis. *, ** and *** denote statistically significant levels at 10%, 5% and 1% respectively.