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Sustainable investments in volatile times: Nexus of climate change risk, ESG practices, and market volatility

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ABSTRACT

Climate change poses an unprecedented threat to global stability, presenting complex political, economic, and social risks. As financial markets become increasingly intertwined with sustainability considerations, understanding the implications of climate risk is paramount. This study investigates the relationships between climate change risk (CCRISK), environmental, social, and governance (ESG) factors, and the United Kingdom's stock market volatility (SMVOL). Using data from 2012 to 2021, we employ a robust analytical approach, including ordinary least squares and a generalised method of moments, to assess these relationships. Our findings reveal several key insights. First, we prove a positive and statistically significant relationship between CCRISK and SMVOL, indicating that firms with higher CCRISK tend to exhibit higher SMVOL. Second, we demonstrate a negative and statistically significant relationship between ESG scores and SMVOL, suggesting that firms with higher ESG scores tend to experience lower SMVOL. Furthermore, we introduced a moderation analysis examining how specific ESG dimensions moderate the CCRISK-SMVOL relationship. Our results reveal nuanced interactions, emphasising that different ESG dimensions influence the relationship differently. The findings offer strategic insights for investors, policymakers, and the advancement of sustainable finance.

1. Introduction

The impacts of climate change, including more frequent extreme weather events, rising sea levels, and disruptions to ecosystems, are expected to profoundly affect the global economy and financial markets (Chenet, 2021). Recent IPCC reports estimate that under a high emissions scenario, global GDP could be reduced by over 7% per year by 2100 (IPCC, 2022). In addition, up to $69 trillion of assets are at risk if global temperatures rise by 3.2 °C (IPCC, 2022). Investor exposure to such climate-related risks has led to growing interest in environmental, social, and governance (ESG) practices as a way to build resilience and mitigate risks. Global sustainable investing assets reached $30.3 trillion in 2022 and have seen rapid growth in Europe and the UK, with assets increasing from $12 trillion in 2020 to $14 trillion in 2022 and the UK taking an increased proportion of global sustainable assets from 34% to 46% (GSIA, 2022).

Since COP26, the UK has continued climate action through regulations like mandatory Task Force on Climate-Related Financial Disclosures (TCFD) disclosures, ESG fund labelling, and transition plans, aiming to increase transparency in sustainable investing, which saw record flows in 2021 with sustainable funds gaining £37.1 billion.[1] Despite a positive perception of ESG practices, investors and academia are still engaged in an ongoing debate about the impact of ESG participation on firm value and the role of climate change risk (hereafter CCRISK), emphasising the need for more refined theoretical efforts to comprehend the insurance mechanisms underlying this firm strategy and its connection to financial market participants.[2]

As we confront a world loaded with environmental and social challenges, this study contributes to a deeper understanding of how responsible business practices and climate risk considerations can enhance market stability. It guides us toward a more sustainable and resilient financial landscape as financial markets have become increasingly intertwined with sustainability considerations. Investors and policymakers are seeking to understand the multifaceted relationship

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[1] See https://esgclarity.com/sustainable-fund-inflows-outdo-wider-market-in-2021/.

[2] See Bagh et al. (2024); Chenet et al. (2021); Greenwood and Warren (2022); Khalfaoui et al. (2022); Mbanyele and Muchenje (2022); Naseer et al. (2023); Ozkan et al. (2022); Sautner et al. (2023a, 2023b); Venturini (2022); Wang and Li (2023); and Xu et al. (2022).

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between corporate actions, ESG factors, and the stability of stock markets (Campiglio et al., 2018; Chenet et al., 2021; Ma et al., 2022; Stroebel & Wurgler, 2021; Wang & Li, 2023). However, the current financial landscape is experiencing a paradigm shift characterised by the rapid evolution of global political and economic frameworks due to globalisation and digitalisation.

A growing body of empirical evidence suggests that CCRISK can exert influence across various dimensions of financial systems, including energy price volatility (Liang et al., 2022), stock market volatility (hereafter SMVOL) (Khalfaoui et al., 2022), exchange market volatility (Bonato et al., 2023), the decision-making processes of firms and investors (Chen et al., 2023), firm performance/value (Naseer et al., 2024; Ozkan et al., 2022; Siddique et al., 2021), cost of sovereign borrowing (Beirne et al., 2021), corporate social responsibility (CSR) (Huang & Lin, 2022; Lins et al., 2017; Mbanyele & Muchenje, 2022), corporate leverage adjustments (Hossain & Masum, 2022), CEO equity incentives (Hossain et al., 2022) and cost structure decisions (Kim et al., 2023). Notably, regulatory authorities, exemplified by the head of the Bank of England, Mark Carney, have underscored the links between CCRISK and financial stability (Carney, 2015). These risks are no longer the rare statistical outliers but have become the norm, manifesting as a continuous stream of crises, for instance, the GFC (Global Financial Crisis) of 2007, the pandemic (COVID-19), and geopolitical tensions like the Russian attack on Ukraine (Kiesel & Stahl, 2023). In this context of systemic risks, the most significant challenge confronting us today is climate change (Wagner & Weitzman, 2015). It stands out as uniquely global, long-term, irreversible, and uncertain. The magnitude of climate change's effects on societal, political, and economic aspects has been meticulously detailed in the "Intergovernmental Panel on Climate Change" (IPCC) reports, emphasising its systemic nature (IPCC, 2022, 2023).

The vulnerability of corporate production processes to natural disasters amplified by climate change can impact corporate profits. This poses a unique challenge, as markets have limited experience in addressing such risks, potentially resulting in under-reaction (Hong et al., 2019). Despite this, there remains a gap in previous literature to investigate the crucial matter of how information pertaining to climate risks is factored into stock pricing and volatility (Wu et al., 2022). To mitigate this, regulatory bodies advocate for both voluntary and mandatory disclosures of CCRISK exposures by corporations (Hong et al., 2019). Studies suggest that companies with a strong commitment to CSR have lower levels of risk. This is because their CSR reputation helps them withstand financial difficulties (Albuquerque et al., 2019; Hoepner et al., 2018). Different investor responses to pollution and climate change information can lead to predictable returns (Hong et al., 2019; Krüger, 2015). Investors tend to hold onto stocks of socially responsible companies and funds because of factors like social reputation and liquidity, which affect stock prices (Hsu et al., 2023), and are hesitant to sell stocks with high CSR/ESG ratings but are more willing to sell stocks with low CSR/ESG ratings (Cao et al., 2019; Hartzmark & Sussman, 2019; Renneboog et al., 2008; Riedl & Smeets, 2017). The reasons for this tendency may include liquidity and funding risk (Hsu et al., 2023); these preferences may result in significant liquidity costs.

Understanding financial market dynamics, especially SMVOL, is crucial for investors and policymakers (Asgharian et al., 2023). Scholars explore SMVOL determinants, focusing on CCRISK and ESG considerations. Climate change prompts businesses to address environmental challenges, while ESG, encompassing social and governance factors, affects corporate performance and stock market dynamics. ESG represents a blend of environmental, social, and governance activities within firms, with each component holding significance for stakeholders. Social and environmental responsibility enhances a firm's goodwill and acts as insurance during critical situations (Godfrey, 2005). Transparency through environmental and social disclosures fosters trust among stakeholders (Benlemlih et al., 2018; Chollet & Sandwidi, 2018). Firms prioritising environmental protection can mitigate market risks through pollution control and trading provisions. Shareholders in financial markets penalise firms with high environmental pollution and social negligence, leading to increased firm SMVOL (Wu & Hu, 2019). Prior studies on the ESG-financial risk nexus have yielded positive, negative, mixed, and inconclusive findings (Benlemlih et al., 2018; Cui et al., 2017; Nguyen & Nguyen, 2015; Sassen et al., 2016). Yet, despite the rising importance of ESG in corporate contexts, there is limited research examining the implications of SMVOL for ESG-rated firms outside of the US (United States), Canada (Sabbaghi, 2023) and China.

Recent literature has also noted that market value fluctuations of high and low-ESG-ranked funds are associated with stock volatility (Cerqueti et al., 2021). Higher volatility risk for ESG-rated firms reflects heightened uncertainty in the ESG context, affecting risk-return tradeoffs, social impact, and economic welfare (Avramov et al., 2022; Naseer et al., 2023). Furthermore, empirical research suggests varying effects of ESG on SMVOL. Some studies indicate that ESG indices exhibit higher SMVOL compared to conventional indices (Ur Rehman et al., 2016), while others discover that high ESG corporations experience lower idiosyncratic and systematic risk (Giese et al., 2019). As Stroebel and Wurgler (2021) indicated, there exists a scarcity of studies investigating the extent to which asset prices accurately incorporate CCRISK.

In light of these multifaceted dynamics, this research seeks to investigate the complex relationships between CCRISK, ESG factors, and SMVOL within the context of the United Kingdom. This study aims to address the following research objectives: First, to investigate the impact of firm-level CCRISK on SMVOL. Second, to examine how ESG factors influence SMVOL. Third, to investigate the moderating role of ESG factors between firm-level CCRISK and SMVOL. Fourth, to explore the interaction between CCRISK, ESG factors, and SMVOL within the context of the United Kingdom's annual firm-level data spanning from 2012 to 2021.

Our empirical analysis leverages a robust set of statistical methods to investigate the relationship between these variables. Initially, we conduct basic statistics to offer a preliminary glimpse into the data. Subsequently, we employ ordinary least squares (OLS) regression analysis to assess the initial relationships. However, recognising the potential for endogeneity and other complexities, we extend our analysis to include the generalised method of moments (GMM) approach. The robustness of results is further strengthened with alternative estimations, estimators, and measures. These techniques provide a more comprehensive and robust assessment of the associations under investigation, considering the time series and cross-sectional dependencies inherent in our dataset. Through a comprehensive analytical framework, this study aims to contribute valuable insights that inform investment strategies, policy development, and our understanding of the evolving landscape of sustainable finance.

The remainder of the paper's structure is as follows. Important literature and theories are discussed in Section 2. Section 3 presents data, econometric models, and study design. The main findings and robustness checks are in Section 4. Section 5 is the conclusion, analysis's implications, and potential research areas.

2. Literature review and hypothesis development

This study significantly contributes to the expanding field of empirical research on climate finance by examining the interplay of CCRISK and ESG factors on SMVOL. This literature review delves into diverse aspects of CCRISK and ESG and their potential impact on the stock market.

2.1. Theoretical underpinning

2.1.1. Climate change risk and stock market volatility

The intersection of CCRISK and SMVOL constitutes a multifaceted phenomenon not fully addressed by specific economic or financial theories. Instead, it can be comprehended and analysed through diverse economic and financial theories and concepts. Recent research has predominantly focused on understanding the relationship between climate change and financial markets, exploring how financial markets may either mitigate or exacerbate climate change-related risks. The impact of CCRISK on asset returns is a subject of considerable debate, where factor models, as outlined by Schwert (1989), provide a comprehensive framework for assessing factors influencing asset returns across different portfolios.[3]

Scholars have examined how CCRISK challenges the Efficient Market Hypothesis (EMH) and affects market efficiency (Fama, 1970). The information asymmetry theory, as proposed by Miller (1977), suggests that investors facing uncertainty due to asymmetric information are prone to higher risk levels and lower stock returns. As companies disclose climate-related concerns, existing stockholders experience heightened uncertainty, resulting in negative stock price changes. This aligns with the information asymmetry mechanism, wherein the revelation of climate risks increases uncertainty and adversely affects stock prices.

Variability in firms' disclosure and transparency regarding climate risks can result in incomplete information for investors, contributing to uncertainty and potential overreaction or under-reaction in stock prices. The Behavioural Finance theory, as emphasised by scholars like Ginglinger and Moreau (2019), posits that investors, becoming increasingly aware of CCRISK, may perceive firms with higher climate risks as riskier investments, influencing market dynamics. This perception of risk can lead to increased uncertainty and volatility in the stock market, in line with the behavioural biases highlighted in Behavioural Finance.

Chava (2014) established early evidence that investors typically demand a higher cost of capital for companies with heightened environmental concerns, aligning with the Capital Asset Pricing Model (CAPM) and the broader cost of capital theories. Recent studies, such as Bolton and Kacperczyk (2021a, 2023); Bouri et al. (2023); Hong et al. (2019); Hsu et al. (2023); Khalfaoui et al. (2022); Lian et al. (2023); Liesen et al. (2017); Lv and Li (2023); Naseer et al. (2023); Zhao et al. (2024), further contribute to this understanding by highlighting the impact of uncertainty in environmental laws and regulations on portfolio returns and the significant sensitivity of the market to climate change risks.

Alessi et al. (2021) concentrate on stock markets, revealing that investors accept lower returns for stocks of companies disclosing environmental data with lower emission intensity. Although global institutional sector losses are not substantial due to the exclusion of second-round effects, reallocating portfolios to greener assets could mitigate these losses. The Portfolio Theory, introduced by Markowitz, suggests that investors optimise their portfolios to achieve the maximum return for a given level of risk. In the context of climate change, investors may reallocate portfolios to minimise risk and optimise returns.

Considering the profound influence of climate change on businesses, it becomes imperative for asset prices to accurately reflect the vulnerability of cash flows to climate-related risks. Uncertainties introduced by CCRISK, encompassing physical, transition, and liability risks, can elevate market volatility, prompting investors to reassess portfolios and risk tolerance. Evolving regulations addressing climate change concerns, potential adverse effects on profitability, and uncertainties surrounding the transition to a low-carbon economy contribute to higher SMVOL. Companies vulnerable to climate-related physical risks may face adverse financial impacts, leading to sudden shocks and increased SMVOL. The mechanism here involves unexpected events driven by physical risks, influencing investor reactions, and contributing to elevated volatility. According to Giglio et al. (2021), transition risks, such as uncertainties in adapting to a low-carbon economy, can also contribute to increased volatility.

The underlying theoretical framework integrates perspectives from the EMH, Behavioural Finance, CAPM, Portfolio Theory, and information asymmetry, providing a comprehensive understanding of how CCRISK impacts SMVOL through various mechanisms.

2.1.2. ESG and stock market volatility

The theory of sustainable development posits that a favourable performance in ESG criteria signifies that businesses prioritise standardised practices and sustainable development. This orientation can prove appealing to prospective customers, suppliers, and partners who share a commitment to sustainable principles. Consequently, this approach helps organisations steer clear of myopic strategies in their business development endeavours while concurrently mitigating a wide spectrum of potential risks (Chen et al., 2022).

Legitimacy theory presents a valuable framework for comprehending the association between ESG considerations and the volatility of firm stock prices. ESG actions undertaken by firms are deemed legitimate activities. “Legitimacy is a generalised perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions” (Suchman, 1995, p. 574). Prior scholarly investigations in the realm of CSR have placed significant emphasis on the legitimacy theory, establishing it as a widely adopted framework for elucidating firms' disclosures regarding environmental and social aspects (Campbell et al., 2003; Deegan, 2002). Legitimacy theory postulates the existence of a societal contract between a firm and the society within which it operates. Firms tend to disclose comprehensive information about their environmental and social initiatives to mitigate information asymmetry and foster trust among stakeholders. Failure to engage effectively in ESG activities may be construed as a lack of conscientiousness on the part of firms regarding societal and environmental issues. Such negligence can lead to punitive measures imposed by society, thereby jeopardising the firm's survival (Deegan, 2002). It is essential to underscore that the ESG responsibility standard underscores the imperative for enterprises to adhere strictly to legal regulations. Furthermore, positive ESG performance plays a pivotal role in augmenting the legitimacy of corporate organisations, engendering trust, and garnering support from governmental bodies and regulatory authorities. This, in turn, not only lowers the prospective regulatory pressures and the likelihood of violations for enterprises (Reber et al., 2022) but also facilitates access to crucial resources, such as government subsidies, thereby mitigating firm-level risks.

Stakeholders have the capacity to penalise firms during crises by diminishing demand for products and services, disrupting supply chains, and prompting investor capital withdrawal (Deegan, 2002). These actions can significantly impact a firm's stock performance, escalating financial risk and SMVOL. The stakeholder theory underscores the valuable influence of actively fulfilling ESG responsibilities. This proactive approach enhances their public image, fosters moral capital, and accumulates reputation, which acts as a protective “insurance effect.” This reputational capital assists firms in navigating external adversities more smoothly, reducing uncertainties in business processes and, consequently, mitigating risks.

Hence, it is imperative for companies to legitimise their actions during crises, establish objectives aligned with stakeholder expectations, and embrace sustainable development initiatives. These steps not only attract potential consumers, suppliers, and partners who prioritise sustainable practices but also deter shortsighted behaviour in business development and comprehensively reduce various potential risks (Sabbaghi, 2023). The availability of enterprise resources plays a pivotal role in a company's ability to manage uncertainties in production and operations and address firm-level risks (Tan & Gümüşburun Ayalp, 2022). Positive performance in ESG factors helps companies acquire the necessary resources to mitigate risks effectively (Bagh et al., 2024; Naseer et al., 2024).

As per the asymmetric information theory, enterprises exhibiting positive social responsibility performance can enhance information transmission to market investors. This is achieved through the disclosure

[3] A detail review provided by Venturini, A. (2022).

of specific non-financial data, encompassing ESG aspects, thereby elevating information transparency (Brammer & Millington, 2008; He et al., 2024; Pedersen et al., 2021). Consequently, this contributes to a reduction in the degree of information asymmetry. By doing so, companies bolster their ability to access credit resources in the capital market and mitigate risks associated with fund shortages.

2.2. Hypotheses development

Our study examines the relationship between CCRISK and SMVOL. This contributes to the ongoing discussion on whether capital markets systematically incorporate and value CCRISK. Matsumura et al. (2014) examined the impact of direct carbon emissions on the firm's value in an initial study. Based on an analysis of S&P 500 companies from 2006 to 2008, researchers discovered a negative relationship between higher emissions and firm values. Chava (2014) delves into the connection between the company's environmental track record and the costs linked to obtaining equity and loans. In his research, he discovered that investors anticipate greater returns from businesses that have been excluded from environmental assessments due to climate change worries, as determined by the projected cost of capital derived from analyst earnings predictions.

Berkman et al. (2019); Naseer et al. (2024) employ a company-specific climate risk metric, which they discover to have an inverse relationship with firm value. Hsu et al. (2023) find a positive relationship between the level of pollution generated by organisations and their exposure to environmental regulation risk, leading to higher average returns. In their study, Görgen et al. (2021) developed a carbon risk factor and calculated carbon beta for companies. According to Monasterolo and de Angelis (2020), the market has perceived low-carbon indicators as less risky following the announcement of the Paris Agreement. However, financial markets show a less significant response to carbon-intensive indicators. A recent comprehensive study by Bolton and Kacperczyk (2021a, 2021b) demonstrated that there is a correlation between carbon premium and carbon emissions. A notable finding is that there is no correlation between it and emission intensity. The latest studies by Bolton and Kacperczyk (2021a); Bouri et al. (2023); Li et al. (2023); Monasterolo and de Angelis (2020) concur that financial markets exhibit an uneven response to CCRISK.

Other studies are more critical of the effectiveness of pricing CCRISK. According to Liesen et al. (2017), financial markets seemed ineffectual in pricing publicly accessible information on carbon emission disclosure and performance. Hong et al. (2019) observe a partial integration of CCRISK in the stock prices of food companies.

In the first strand of papers, climate change is measured directly by the increase in temperature and its climatic consequences, such as the increase in the frequency of extreme events, e.g. (Balvers et al., 2017; Coumou & Rahmstorf, 2012; Gregory, 2021). Another body of literature, which comprises the majority of research (Bolton & Kacperczyk, 2021a, 2021b; Bouri et al., 2023; Li et al., 2023; Matsumura et al., 2014), examines the extent to which businesses are affected by climate change by assessing their carbon emissions, whether direct or indirect. According to Giglio et al. (2021), one major difficulty in calculating these consequences is that it is difficult to determine how specific businesses are impacted by climate change since the effects are complex and come from several sources. By introducing a measure for the exposure of firms to CCRISK,[4] Sautner et al. (2023a) created time-varying metrics of how call participants from all around the world perceive companies' exposures to various aspects of climate change using transcripts of earnings conference calls. They interpreted these measurements to reflect the current level of interest that management and financial analysts have in climate change-related issues. These metrics have the advantage of reflecting "soft" information from management and analyst information exchanges. Unlike the previous literature, in this research, we employ firm-level CCRISK measures developed by Sautner et al. (2023a).

In the existing literature, some studies indicate that firms with high exposure to climate change may experience lower returns due to delayed incorporation of climate information into stock prices Xu et al. (2022); others suggest a complex relationship between CCRISK and asset returns, with factors such as emissions, environmental profiles, and regulatory risks playing key roles (Berkman et al., 2019; Bouri et al., 2023; Chava, 2014; Görgen et al., 2021; Hsu et al., 2023; Matsumura et al., 2014; Sautner et al., 2023b). However, there is ongoing debate regarding whether financial markets efficiently price CCRISK, with some studies finding ineffective pricing (Hong et al., 2019; Liesen et al., 2017) and some concluding with insignificant CCRISK and SMVOL relationship (Li et al., 2023). Based on the above discussion, we hypothesise that.

Hypothesis 1. Climate change risk positively influences stock price volatility.

ESG represents a firm's sustainability practices. Stakeholders value a firm's ESG practices/involvement, and any lack of responsiveness in ESG activities can harm a firm's financial performance, potentially leading to increased SMVOL. Previous research has consistently indicated that businesses having strong ESG practices/involvement are exposed to reduced economic risk across various industries (Benlemlih & Girerd-Potin, 2017; Sassen et al., 2016; Wang et al., 2023). Benlemlih et al. (2018) discovered that ESG disclosures have a significant negative influence on both overall risk and idiosyncratic risk. This negative effect is attributed to the increased corporate transparency resulting from these disclosures, which enhances stakeholders' trust and reputation. Trust among stakeholders plays a pivotal role in diminishing a firm's overall risk. Chollet and Sandwidi (2018) identified a harmful effect of social and governance attributes on risk (financial risk). This relationship is attributed to good governance practices and improved environmental initiatives within firms. Wu and Hu (2019) investigated the Chinese energy sector's CSR impact on the risk associated with stock price crashes and identified an adverse CSR-crash risk association. This outcome is associated with energy firms' enhanced CSR performance, particularly in areas for instance, environmental security, the company's image, and technological innovation. By prioritising environmental protection, energy firms can mitigate crash risk. Pollution improvement and trading provisions serve as insurance against stock price crash risk.

On the contrary, several research studies found a significant positive impact of CSR strengths and CSR concerns on SMVOL (Kölbel et al., 2017; Nguyen & Nguyen, 2015; Quan et al., 2015). These studies highlighted a positive relationship between CSR and firm risk, explaining it as a trade-off between the claims of a firm's employees and shareholders. When firms prioritise employees over shareholders, the risk may shift toward stockholders/owners (Nguyen & Nguyen, 2015). The study of Kölbel et al. (2017) revealed a positive effect of corporate social irresponsibility on risk, noting that adverse information/news about ESG concerns can increase financial risk.

Empirical research shows that companies with strong ESG practices tend to have lower systemic, tail, and downside risks. Heinkel et al. (2001) and Chen et al. (2001) found that ESG reduces systemic risk. Diemont et al. (2016); Mishra and Modi (2013); Sassen et al. (2016) showed ESG lowers tail risk. Albuquerque et al. (2018); Lueg et al. (2019) demonstrated that ESG decreases corporate risk. Ilhan et al. (2020) linked weak ESG to higher tail risks. Cojoianu et al. (2020) revealed that ESG reduces downside risk during crises. Krueger et al. (2021); Lins et al. (2017) found high ESG firms recover quicker from adverse events and show resilience during crises. Studies found high ESG firms experienced more stable stock returns (Zhang et al., 2020), reduced volatility (Sabbaghi, 2023; Shakil, 2022), lower negative skewness (Albuquerque et al., 2020), and favourable valuations (Oikonomou et al., 2012). Overall, empirical evidence shows robust ESG standards mitigate systemic, tail, and downside risk through product differentiation, demand stabilisation, favourable valuations, and

[4] For detail methodology see Sautner, Van Lent, Vilkov, and Zhang (2023a).

resilience.

ESG constitutes a forward-looking, long-term strategy for firms with expected future benefits. However, short-term investors seek immediate returns on their investments. When they believe that a company is not generating immediate profits, they often withdraw their capital and seek other investment opportunities, which could potentially contribute to market instability. Conversely, socially responsible investors give precedence to a firm's social and environmental credibility over short-term gains, showcasing their high ethical awareness. These ethically and socially responsible investors contribute to the outperformance of firms with strong ESG performance in the market. Even during financial downturns and pandemics, such firms maintain market stability. Based on these insights, this study proposes the following hypothesis:

Hypothesis 2. Increased ESG practices significantly decrease stock price volatility.

Increased engagement by firms in ESG practices is expected to alleviate the adverse effects of CCRISK on SMVOL through reputation-building and social capital channels. Prior research has shown that ESG initiatives can help buffer against negative reactions from stakeholders during challenging times by signalling a firm's dedication to safeguarding its stakeholders from detrimental impacts (Christensen, 2016; Flammer, 2013). Engaging in ESG activities during crisis periods tends to be positively received by society, consequently bolstering a firm's corporate image and fostering a favourable perception among stakeholders (Qiu et al., 2021). Considering that CCRISK heightens societal consciousness regarding environmental issues and the demand for reputation assurance, we contend that investments in ESG can mitigate the adverse consequences of CCRISK on SMVOL through the mechanism of reputation insurance.

While strategies to adapt to CCRISK are commonly associated with environmental practices, the social dimension of ESG engagement can also hold relevance, particularly in countries vulnerable to crises and risks, including those stemming from climate change. Chemmanur et al. (2022) emphasise the pivotal role of ESG engagement in influencing firm survival, especially in adverse climate conditions. Their findings lend support to the argument that firms with more extensive ESG engagement are not only more likely to endure in the long term but are also less prone to being delisted when confronted with extreme weather events. Additionally, they discovered that high-ESG firms encounter fewer capital constraints and enjoy improved access to finance, thereby enhancing their resilience during periods of heightened uncertainty. In a similar vein, He et al. (2022) report that involvement in ESG activities during natural disasters ultimately led to superior financial performance compared to non-disaster periods. Lins et al. (2017) conducted a comparative analysis of stock market performance between firms with high and low ESG scores, positing that strong social capital becomes particularly valuable during periods characterised by unexpectedly low trust, such as the global financial crisis.

More recently, Ozkan et al. (2022) examined the moderating role of ESG scores in the relationship between CCRISK and a firm's financial outcomes. They argue that firms can mitigate the adverse impact of CCRISK on their accounting performance by investing in ESG initiatives. In alignment with the arguments presented above, we formulate our hypothesis as follows:

Hypothesis 3. Greater ESG engagement reduces the negative impact of climate risk on stock market volatility.

2.3. Conceptual framework

The study's conceptual framework integrates key economic and financial theories to elucidate the interplay between CCRISK and ESG factors in influencing SMVOL. Drawing on the EMH, information asymmetry theory, and Behavioural Finance, the CCRISK dimension recognises challenges to market efficiency as climate-related concerns unfold. The CAPM and Portfolio Theory inform the understanding of how CCRISK affects the cost of capital and prompts portfolio reallocation. Physical, transition, and liability risks associated with climate change contribute to heightened SMVOL, influenced by regulatory uncertainties and financial shocks. Simultaneously, within the ESG domain, sustainability, legitimacy, and stakeholder theories reveal that positive ESG practices foster trust, reduce information asymmetry, and act as a protective "insurance effect" during crises. Empirical evidence supports ESG's role in mitigating systemic, tail, and downside risks, enhancing corporate resilience. The conceptual framework posits that increased ESG engagement could potentially alleviate the adverse effects of CCRISK on SMVOL, supported by research indicating ESG's role as a buffer during challenging times and its positive impact on a firm's financial outcomes.

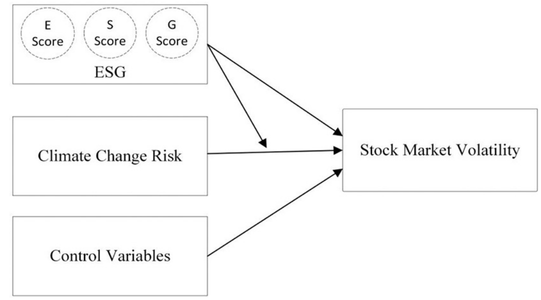

Fig. 1. Conceptual framework.

The buffer effect of ESG practices during crises aligns with stakeholder theory, where firms actively fulfilling ESG responsibilities foster a positive public image, accumulate reputation, and navigate external adversities more smoothly. The conceptual framework, guided by these key theories, positions ESG as a strategic tool that not only improves a firm's long-term prospects but also moderates the adverse impact of CCRISK on SMVOL through reputation-building and social capital channels. Fig. 1 depicts the conceptual framework of the study. This section sets the stage for empirical analysis, enriching the theoretical landscape of sustainable finance and providing valuable insights for both scholars and practitioners.

3. Methodology

This section presents data samples, variable descriptions, empirical model settings, and methods used to attain study objectives.

3.1. Data and sample description

We employ a quantitative methodology to examine a dataset consisting of 488 publicly listed companies in the United Kingdom spanning the years 2012 to 2021. In the initial phase, we gathered climate change exposure data[5] and matched it with ESG combined and individual dimension data from LSEG (formally Refinitiv) using various company identifiers. Following this, financial and stock market data for these companies were sourced from CompuStat and Bureau van Dijk Fame. Our final sample was carefully selected based on criteria such as excluding companies with insufficient data, limiting the analysis to firms disclosing ESG scores, and removing observations with negative total assets or equity. Additionally, outliers and firms with zero or negative common equity were omitted. To ensure robustness, key variables are winsorized at the 1st and 99th percentiles to address the potential

[5] Data available at https://doi.org/10.17605/OSF.IO/FD6JQ.

influence of outliers. The sample period has been governed by data availability. This rigorous approach to sample selection and data collection sets the stage for a thorough quantitative exploration of the research hypotheses.

3.2. Variables description

In the case of publicly traded companies, the stock market's performance serves as a direct reflection of investors' outlook regarding the firm's future earnings, as noted by (He et al., 2023). This study employs stock returns as a measure of SMVOL, where stock returns are computed as the natural logarithm of the current month's price[6] divided by the previous month's price. SMVOL is then determined as the annual standard deviation of these monthly stock returns.[7] Annual SMVOL is calculated as the square root of the sum of squared monthly returns within a calendar year. A higher value of this indicator signifies an elevated level of risk exposure for the firm (He et al., 2023; Paye, 2012).

Building upon the methodology proposed by Bouri et al. (2023); Lv and Li (2023); Noh and Park (2023); Wang and Li (2023); Zhang et al. (2023), we compute SMVOL using the Eq. (1):

$$SMVOl_{i,t} = \sum_{j=1}^{D_{i,t}} r_{i,t,j}^{2} \tag{1}$$

Where ($D_{i,t}$) represents the number of trading days in the (t) month for the (i) firm, and ($r_{i,t,j}$) is the (j^{th}) monthly return on the (i) firm in the (t) year.

We use Sautner et al. (2023a) CCRISK data.[8] Sautner et al. (2023a) created time-varying metrics for how call participants from all around the world perceive companies' exposure to various aspects of climate change using transcripts of earnings conference calls. They interpreted these measurements to reflect the current level of interest that management and financial analysts have in climate change-related issues. These metrics have the advantage of reflecting "soft" information from management and analyst information exchanges. Unlike the previous literature, in this research, we employ firm-level CCRISK measures developed by (Sautner et al., 2023a).

ESG investment factors are critical drivers of portfolio risk and return and ultimately lead to profit maximisation (Gillan et al., 2021). According to previous studies, the ESG indicators from LSEG (formerly Refinitiv) provide a close approximation of a company's performance on environmental, social, and governance factors (Kim et al., 2021). We used the overall and individual environmental, social, and governance performance scores. For ESG scores, LSEG gathers information from diverse sources, including CSR reports, sustainability reports, annual reports, company websites, and proxy filings. For each company, a comprehensive set of over 630 data points is compiled, which are then synthesised into more than 186 key performance indicators (LSEG, 2023). These indicators are further organised into ten categories and grouped under three pillars: environment, social, and corporate governance. Utilising z-scoring, which ranges between 0 and 100%, the scores are normalised, equally weighted, and compared against the entire universe of companies.[9] Furthermore, environmental, and social categories are benchmarked against the LSEG Business Classifications and governance categories against the country of incorporation. The LSEG ESG scores adopt a data-driven approach, incorporating the most pertinent industry metrics while minimising biases related to company size and transparency (LSEG, 2023).

Following most of the risk-related literature, e.g. (Albuquerque et al., 2018; Hossain & Masum, 2022; Lins et al., 2017; Ozkan et al., 2022; Sautner et al., 2023a), we included a set of control variables; firm size, return on assets (ROA), Tobin's q ratio (TQR), profit margin (PM) and R&D investment. Firm size was measured through the natural log of total assets, Tobin's Q ratio, ROA, PM, and R&D investment obtained from Bureau van Dijk Fame. R&D was measured through the natural log of R&D investment. Firm size reflects potential variations in risk due to the scale of operations, while ROA accounts for profitability and operational efficiency. TQR captures market expectations about a firm's future prospects, PM controls for profit margin impact on risk assessments, and R&D investment signals commitment to innovation and growth. The inclusion of these controls aligns our study with established research practices, ensuring comparability and contributing to a more nuanced understanding of the relationship between the main variables of interest and risk.

3.3. Endogeneity concerns

Baseline results are subject to endogeneity issues and, therefore, cause biased estimates. Models like GMM provide better estimates to deal with endogeneity. We have applied the Arellano-Bond dynamic panel model with a finite sample correction to the covariance matrix, following the method proposed by Windmeijer (2005) using the xtabond2 command in Stata to address potential endogeneity concerns. In our analysis, we used instruments based on the framework outlined by Roodman (2009)[10] for dynamic panel estimation. The two-step system GMM model, recognised for robustness against various endogeneity forms, employs GMM-style instruments. In Stata, we implemented the Arellano-Bond dynamic panel model using the xtabond2 command with the following syntax:

```
xtabond2 y l.y x1 x2, x3 x4 twostep robust nomata iv(x1 x2, x3, x4) gmm(l.y lag(##) , collapse)
```

In this command, 'l.y' represents lagged values, serving as regressors in the two-step dynamic framework to handle endogeneity. The lag (# #) expression allows for the inclusion of the desired number of lags in the model. To ensure the validity of these instruments, we conducted tests for serial correlations in the error terms of the differenced equations. Post-estimation, the *"estat sargan"* command computed Sargan test values, while "*estat abond*" conducted the Arellano-Bond test in the first order, ensuring the reliability of our model.

3.4. Econometrics models specification and empirical strategy

In the initial phase, we performed descriptive statistics and correlation analysis. We utilised the Variance Inflation Factor (VIF) to identify potential multicollinearity in the regression. Addressing concerns of serial/autocorrelation and heteroskedasticity, we applied OLS with robust and cluster options, following the guidance of Shen et al. (2016). The equation for the regression model is as follows

[6] Monthly stock prices data obtained from the Bureau van Dijk Fame.
[7] Similar approach as Noh and Park (2023).
[8] Data available at https://doi.org/10.17605/OSF.IO/FD6JQ.
[9] For detail information see https://thesource.refinitiv.com/thesource/getfile/index/4933f0a6-476e-4a30-adbb-df8043d2c33f.
[10] Detail methodology and addressing various concerns related to endogeneity outlined in Roodman (2009).

$$SMVOL_{i,t} = \alpha + \beta_1 CCRISK_{i,t} + \beta_2 ESG_{i,t} + \gamma(SIZE, TQR, ROA, PM, R\&D)_{i,t} + \varepsilon_{i,t} \quad (2)$$

Given the prevalent issue of endogeneity in corporate finance and economics literature, arising from correlated independent variables and error terms or the potential impact of dependent variables on certain independent factors, leading to endogeneity or reverse causality (Pu, 2022), we employed simultaneous equations estimation for panel data to assess the proposed hypotheses, utilising the "step system GMM." Panel data facilitates the examination of company behaviour over multiple years, analysing observations of the same firms across consecutive periods. This approach enriches the study by incorporating the temporal dimension of the data, especially during periods of significant change, allowing control for year-specific factors influencing our study variables. Consequently, we estimated the models using the GMM due to its ability to address endogeneity, a challenge where SMVOL, a firm's CCRISK, and ESG practices may influence each other simultaneously. Instrumental variable methods within the GMM framework were employed to tackle this endogeneity issue. To account for unobservable heterogeneity, the GMM decomposes the random error term (εi) into two components: the pooled effect (μit), which varies across individuals and time periods, and the individual effect (ηi), specific to each company. With these considerations in mind, we examined the bidirectional relationship between CCRISK, ESG, and volatility using the following two-step GMM equations. Finally, to validate our estimations, we conducted a robustness check. The general equation for the GMM is as follows:

$$Y_{i,t} = \alpha_0 + Y_{i,(t-2)} + \beta_1 X_{i,t} .. \beta_3 X_{i,t} + \delta_1 X_{i,t}(Controls) ..... \delta_1 X_{i,t}(dumy) + \varepsilon_{i,t} \quad (3)$$

We use the precise specifications of the GMM models to investigate the direct relationship between CCRISK, ESG, and volatility.

$$SMVOL_{i,t} = \alpha_0 + \beta_1 CCRISK_{i,t} + \beta_2 ESG_{i,t} + \delta\,(CONTROLS)_{i,t} + V_I dum\ year + \eta_1 dum\ industry + \varepsilon_{i,t} \quad (4)$$

We use the following equations to investigate the moderating relationship of ESG between firms CCRISK and SMVOL.

$$\begin{aligned} SMVOL_{i,t} = {} & \alpha_0 + \beta_1 CCRISK_{i,t} + \beta_2 ESG_{i,t} + \beta_3 (CCRISK{*}ESG)_{i,t} \\ & + \delta\,(CONTROLS)_{i,t} + V_I dum\ year + \eta_1 dum\ industry + \varepsilon_{i,t} \end{aligned} \quad (5)$$

$$\begin{aligned} SMVOL_{i,t} = {} & \alpha_0 + \beta_1 CCRISK_{i,t} + \beta_2 ESCORE_{i,t} + \beta_3 (CCRISK{*}ESCORE)_{i,t} \\ & + \delta\,(CONTROLS)_{i,t} + V_I dum\ year + \eta_1 dum\ industry + \varepsilon_{i,t} \end{aligned} \quad (6)$$

$$\begin{aligned} SMVOL_{i,t} = {} & \alpha_0 + \beta_1 CCRISK_{i,t} + \beta_2 SSCORE_{i,t} + \beta_3 (CCRISK{*}SSCORE)_{i,t} \\ & + \delta\,(CONTROLS)_{i,t} + V_I dum\ year + \eta_1 dum\ industry + \varepsilon_{i,t} \end{aligned} \quad (7)$$

$$\begin{aligned} SMVOL_{i,t} = {} & \alpha_0 + \beta_1 CCRISK_{i,t} + \beta_2 GSCORE_{i,t} + \beta_3 (CCRISK{*}GSCORE)_{i,t} \\ & + \delta\,(CONTROLS)_{i,t} + V_I dum\ year + \eta_1 dum\ industry + \varepsilon_{i,t} \end{aligned} \quad (8)$$

The constituents of our models are as follows: SMVOL is stock market volatility; ESG refers to the environmental (ESCORE), social (SSCORE), and governance (GSCORE) index; the letters i and t represent the firms and the year. The ε is the error term, industry fixed effect, and year effect dummy variables. The control variables are firm size, return on assets (ROA), Tobin's q ratio (TQR), profit margin (PM) and the natural log of R&D investment.

4. Empirical results and discussion

4.1. Overview of key findings

In this section, we present the empirical findings obtained from our estimations. Before conducting these estimations, we performed various preliminary tests, including a descriptive analysis, an assessment of the VIF in Table 1, and an examination of correlations in Fig. 2. Table 2 presents baseline OLS regression results with SMVOL as the dependent variable. CCRISK has a positive and significant association with SMVOL across all models. ESG has a negative and significant relationship with SMVOL. The control variables perform as expected. Table 3 shows GMM regression results. Models 1-4 examine the direct relationships. CCRISK retains a positive and significant link with SMVOL. ESG and its components (E Score, S Score, G Score) have negative effects on SMVOL. Models 5-8 incorporate interaction terms and show that CCRISK*ESG and its components are negatively associated with SMVOL, indicating moderation. Figs. 5–8 visualise the moderating effects graphically. The slopes become less steep from low to high values of the moderators, confirming moderation. Table 4 presents robustness checks using alternative estimators and measures. Key findings remain consistent. Overall, the results indicate that CCRISK increases SMVOL while ESG decreases it. Furthermore, ESG dampens the positive CCRISK-SMVOL relationship. The findings are robust across models.

Table 1
Summary Statistics and Variance Inflation Factor.

Variables	Mean	SD	Min	Max	N	VIF	1/VIF
SMVOL	0.311	0.398	0.000	0.956	4880		
CCRISK	0.0002	0.0001	0.000	0.002	4880	1.015	0.985
ESG	0.442	0.396	0.000	0.98	4880	1.080	0.926
SIZE	10.982	5.792	0.000	19.756	4880	1.338	0.748
TQR	0.199	0.78	0.052	1.238	4880	1.354	0.739
ROA	0.904	1.139	0.768	3.04	4880	1.374	0.728
PM	1.141	1.309	0.441	3.855	4880	1.264	0.791
R&D	1.876	3.866	0.000	16.86	4880	1.058	0.945
MEAN VIF						1.212	

Note: The main variables of our study are presented in this table with descriptive statistics and variance inflation factor (VIF). The dataset is composed of years 2012 to 2021, with 4880 firm-year observations from the United Kingdom.

Fig. 2. Pairwise correlations.

Note: Our study's independent and control variables are presented in this figure with pairwise correlation. The dataset is composed of years 2012 to 2021, with 4880 firm-year observations from the United Kingdom.

Table 2

Baseline ordinary least squares results.

Dependent Variable = SMVOL						
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	OLS	OLS	OLS	OLS	OLS Robust	OLS Cluster
CCRISK	0.0205***		0.0165***	0.0171***	0.0171***	0.0171***
	(0.0058)		(0.0059)	(0.0059)	(0.0055)	(0.0056)
ESG		−0.2709***	−0.1992***	−0.2031***	−0.2031***	−0.2031***
		(0.0308)	(0.0437)	(0.0483)	(0.0487)	(0.0609)
SIZE				0.0019	0.0019	0.0019
				(0.0035)	(0.0034)	(0.0038)
TQR				−0.0657***	−0.0657***	−0.0657***
				(0.0217)	(0.0216)	(0.0219)
ROA				0.0032	0.0032	0.0032
				(0.0158)	(0.0159)	(0.0170)
PM				−0.0058	−0.0058	−0.0058
				(0.0145)	(0.0158)	(0.0167)
R&D				−0.0052	−0.0052	−0.0052
				(0.0045)	(0.0041)	(0.0043)
Constant	−1.1481***	−1.0007***	−1.0507***	−1.0665***	−1.0665***	−1.0665***
	(0.0181)	(0.0204)	(0.0279)	(0.0407)	(0.0431)	(0.0580)
Observations	4880	4880	4880	4880	4880	4880
R-Squared	0.0059	0.0209	0.0158	0.0211	0.0211	0.0211

The table provides the estimates of the impact of firm climate change risk (CCRISK) and ESG on stock market volatility (SMVOL). Estimations include OLS, OLS Robust and OLS Cluster standard errors. Below the coefficients, the standard errors are given in parentheses. Asterisks indicate statistical significance at the 10% one-star (*), 5% two-star (**), and 1% three-star (***) levels.

4.2. Preliminary analyses

Table 1 presents summary statistics and VIF for the variables. It shows the mean, standard deviation, minimum, maximum, number of observations, and VIF for each variable.

SMVOL has a mean of 0.311 and a standard deviation of 0.398. CCRISK and ESG have means of 0.0002 and 0.442, respectively. SIZE, TQR, ROA, PM, and R&D show reasonable values. The VIFs are all below 5, indicating no severe multicollinearity issues.

Fig. 2 shows pairwise correlations between the variables. CCRISK and ESG have a positive correlation of 0.15. ESG is positively correlated with SIZE, ROA, PM, and R&D. TQR has negative correlations with ESG, SIZE, and R&D.

Fig. 3 shows the time series distribution of the average CCRISK over the period 2012–2021. The y-axis represents the average CCRISK value, and the x-axis shows the years. The figure depicts how the average CCRISK for firms in the sample changed over the ten years. The figure shows an increasing trend in average climate change risk after 2016. One potential factor contributing to this rise could be the Paris Agreement, which was adopted in 2016. The landmark international accord

Table 3
Main relationship analysis with GMM.

Dependent Variable = SMVOL								
GMM Estimations	Direct Relationship				Moderating Relationship			
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.SMVOL	−0.1003***	0.307***	0.123**	0.104*	0.068	0.273***	0.109**	0.098*
	(0.0117)	(0.063)	(0.054)	(0.056)	(0.049)	(0.065)	(0.053)	(0.053)
CCRISK	0.1094***	0.121***	0.080***	0.068***	0.115***	0.125***	0.108***	0.087***
	(0.0167)	(0.012)	(0.015)	(0.014)	(0.016)	(0.013)	(0.019)	(0.020)
ESG	−0.5829***				−2.102***			
	(0.1562)				(0.209)			
ESCORE		0.226**				−1.056***		
		(0.107)				(0.215)		
SSCORE			−0.714***				−2.029***	
			(0.146)				(0.228)	
GSCORE				−0.909***				−2.103***
				(0.099)				(0.218)
CCRISK*ESG					−0.189***			
					(0.023)			
CCRISK*ESCORE						−0.152***		
						(0.024)		
CCRISK*SSCORE							−0.179***	
							(0.029)	
CCRISK*GSCORE								−0.156***
								(0.035)
SIZE	−0.0001	−0.006	0.000	0.003	−0.000	−0.007	−0.001	0.002
	(0.0060)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
TQR	−0.1655**	−0.101	−0.135**	−0.190**	−0.238***	−0.119	−0.206***	−0.231***
	(0.0742)	(0.080)	(0.062)	(0.074)	(0.072)	(0.080)	(0.068)	(0.085)
ROA	−0.0561**	−0.052*	−0.018	−0.035	−0.020	−0.064**	−0.013	−0.017
	(0.0241)	(0.031)	(0.019)	(0.021)	(0.030)	(0.029)	(0.028)	(0.030)
PM	−0.0548***	−0.089***	−0.083***	−0.070***	−0.056**	−0.081***	−0.059**	−0.064**
	(0.0110)	(0.024)	(0.022)	(0.024)	(0.025)	(0.027)	(0.025)	(0.025)
R&D	0.0279***	0.030***	0.037***	0.030***	0.036***	0.037***	0.038***	0.034***
	(0.0092)	(0.011)	(0.009)	(0.009)	(0.008)	(0.009)	(0.008)	(0.009)
Number of ids	488	488	488	488	488	488	488	488
P value (AR1)	0.0015	0.0024	0.0022	0.0020	0.0022	0.0025	0.0023	0.0024
P value (AR2)	0.1931	0.2582	0.5736	0.5359	0.1346	0.0980	0.1667	0.2693
P value (Sargan)	0.0859	0. 6890	0.0920	0.0827	0.5510	0.5431	0.5201	0.7870

Note: The table provides the estimates of the impact of firm climate change risk (CCRISK) and ESG on stock market volatility (SMVOL) from columns 1–4. and moderating the relationship of ESG between (CCRISK) and (SMVOL) from column 5–8. Estimations include GMM. Below the coefficients, the standard errors are given in parentheses. i) * at the 1%, ** 5%, and *** 10% significance levels. ii) The Arellano–Bond AR1 & AR2 test assesses serial correlation of order i by employing residuals in first differences, with an asymptotic distribution of N (0,1) under the null hypothesis, indicating the absence of serial correlation. iii) The Sargan test evaluates over-identifying restrictions, with an asymptotic distribution following the chi-squared (χ2) distribution under the null hypothesis, indicating no correlation between the instruments and the error term.

on climate change likely placed greater emphasis on climate risk, driving increased attention and disclosures from companies.

Fig. 4 shows a s time series distribution for two variables - average ESG scores and average SMVOL. The y-axis represents the average values for ESG and SMVOL, while the x-axis shows the years from 2012 to 2021. This figure shows how both the ESG scores and SMVOL changed over time for the sample of UK firms. Fig. 4 depicts an overall increasing trend in average ESG scores over the 2012–2021 period. This upward trajectory suggests UK companies have improved their ESG profiles over time, potentially in response to greater sustainability awareness and demand from stakeholders.

In summary, Fig. 3 shows an upward shift in climate change risk post-2016 that may be linked to the Paris Agreement. Fig. 4 exhibits an increasing trend in average ESG scores, indicating improved sustainability performance by firms over a 10-year span.

4.3. Baseline OLS regression estimations

Table 2 presents baseline OLS regression results with SMVOL as the dependent variable. CCRISK has a positive and significant association with SMVOL across all models. The estimations include OLS estimators. The coefficients represent the estimated effects of CCRISK and ESG on SMVOL while controlling for other variables.

The coefficient of CCRISK is positive and statistically significant at the 1% level, indicating that a one-unit increase in CCRISK is associated with a 0. 0165 to 0.0205 units increase in SMVOL, holding all others constant. This suggests that firms with higher CCRISK tend to have higher SMVOL. In existing literature studies, Bouri et al. (2023); Hsu et al. (2023); Ilhan et al. (2020); Noh and Park (2023); Sautner et al. (2023a, 2023b) support positive CCRISK and SMVOL relationship. In the case of ESG, the coefficient for ESG is negative and statistically significant. The coefficient of ESG is negative and statistically significant at the 1% level. This means that a one-unit increase in ESG scores is associated with a 0.2709 to 0.1992 unit decrease in SMVOL, holding all else constant. This suggests that firms with higher ESG scores tend to have lower SMVOL. Stakeholders value a firm's ESG involvement, and any lack of responsiveness in ESG activities can harm a firm's financial performance, potentially leading to increased SMVOL. Previous research has consistently indicated that businesses having strong ESG ratings are exposed to reduced economic risk and SMVOL (Benlemlih et al., 2018; Benlemlih & Girerd-Potin, 2017; PRI, 2016; Refinitiv, 2020; Sassen et al., 2016). This negative effect is attributed to the increased corporate transparency resulting from these disclosures, which enhances stakeholders' trust and reputation. Trust among stakeholders plays a pivotal role in diminishing a firm's SMVOL.

The control variables all have the expected signs, but only TQR is statistically significant. This means that TQR is a crucial factor that is most strongly correlated with SMVOL. The results of this regression

Table 4
Robustness analysis.

Dependent Variable SMVOL	Direct Relationship with Alternative Estimator				Direct Relationship with Alternative Measures			Moderation Analyses	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Variables	PCSE	PCSE	PCSE	PCSE	GMM	GMM	GMM	GMM	GMM
L. SMVOL					0.015	−0.152***	0.241***	−0.119***	0.173***
					(0.030)	(0.025)	(0.054)	(0.025)	(0.048)
CCRISK	0.062***	0.103***	0.071***	0.064***			0.129***		0.131***
	(0.014)	(0.012)	(0.015)	(0.015)			(0.014)		(0.016)
CCEXPO					0.126***	0.137***		0.193***	
					(0.012)	(0.012)		(0.015)	
ESG	−0.804***					−0.464***		−1.613***	
	(0.132)					(0.101)		(0.152)	
ESCORE		−0.243***			0.595***				
		(0.093)			(0.051)				
SSCORE			−0.669***		−0.386***				
			(0.139)		(0.128)				
GSCORE				−0.719***	−0.452***				
				(0.149)	(0.123)				
E&S							0.123		−1.565***
							(0.100)		(0.206)
CCEXPO*ESG								−0.209***	
								(0.024)	
CCRISK*E&S									−0.187***
									(0.027)
SIZE	−0.003	−0.008	−0.004	−0.006	−0.011**	−0.016***	−0.004	−0.005	−0.007
	(0.006)	(0.006)	(0.006)	(0.006)	(0.005)	(0.005)	(0.006)	(0.005)	(0.006)
TQR	−0.065*	−0.058	−0.053	−0.064*	−0.508***	−0.501***	−0.126	−0.561***	−0.171**
	(0.034)	(0.038)	(0.036)	(0.036)	(0.041)	(0.041)	(0.082)	(0.041)	(0.082)
ROA	−0.050	−0.069**	−0.060*	−0.060*	−0.032**	−0.045***	−0.054*	−0.033**	−0.056**
	(0.033)	(0.035)	(0.033)	(0.033)	(0.016)	(0.016)	(0.028)	(0.016)	(0.027)
PM	0.045*	0.039	0.043*	0.051**	−0.052***	−0.046***	−0.091***	−0.030**	−0.070***
	(0.024)	(0.026)	(0.025)	(0.025)	(0.015)	(0.015)	(0.022)	(0.014)	(0.025)
R&D	0.002	−0.002	−0.001	−0.000	−0.003	−0.001	0.033***	0.001	0.039***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.005)	(0.005)	(0.011)	(0.005)	(0.009)
P value (AR1)					0.0000	0.0000	0.0020	0.0010	0.0022
P value (AR2)					0.8593	0.0900	0.4163	0.0531	0.1692
P value (Sargan)					0.6301	0.2654	0.1869	0.1781	0.1652

Note: * at the 1%, ** 5%, and *** 10% significance levels. The Arellano–Bond AR1 & AR2 test assesses serial correlation of order by employing residuals in first differences, with an asymptotic distribution of N (0,1) under the null hypothesis, indicating the absence of serial correlation. The Sargan test evaluates over-identifying restrictions, with an asymptotic distribution following the chi-squared ($\chi2$) distribution under the null hypothesis, indicating no correlation between the instruments and the error term.

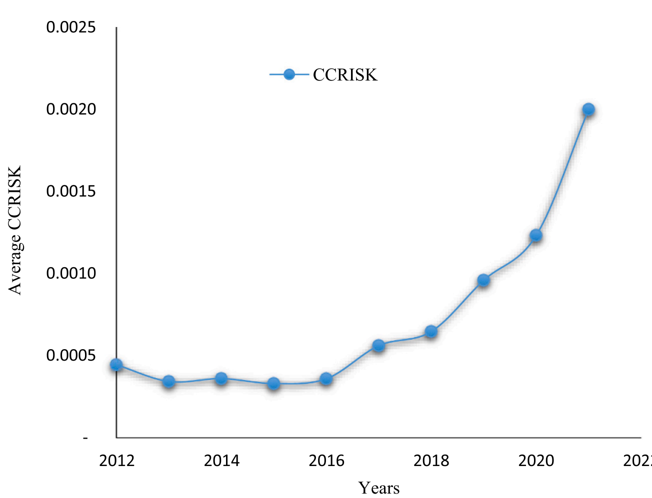

Fig. 3. Average CCRISK from 2021 to 2022.
Note: The time series distribution of average CCRISK is presented in this figure. The Y-axis represents the Average CCRISK, and the X-axis represents years. The dataset is composed of years 2012 to 2021, with 4880 firm-year observations from the United Kingdom.

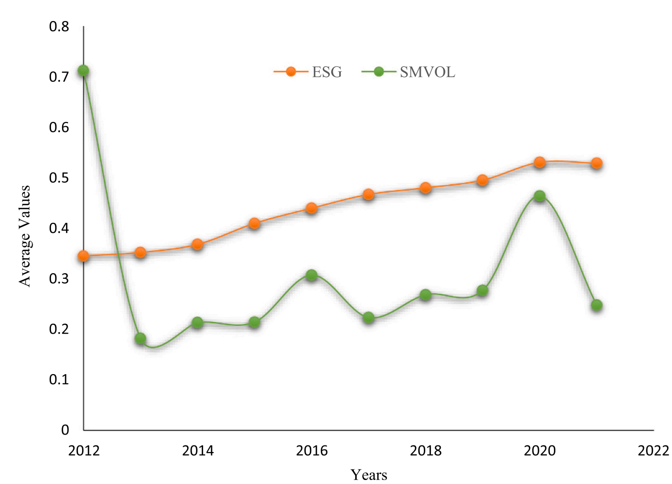

Fig. 4. Average ESG and SMVOL from 2021 to 2022.
Note: The time series distribution of average ESG and SMVOL is presented in this figure. The Y-axis represents the average ESG/SMVOL and X-axis years. The dataset is composed of years 2012 to 2021, with 4880 firm-year observations from the United Kingdom.

analysis suggest that CCRISK and ESG are positively and negatively correlated with SMVOL, respectively. This means that firms with higher CCRISK and ESG scores tend to have higher and lower SMVOL, respectively. These findings have important implications for investors and policymakers. Investors should consider CCRISK and ESG scores when making investment decisions. Policymakers should develop policies that promote sustainable and responsible business practices, which can help to reduce SMVOL.

4.4. Direct relationship analysis with GMM

We used Arellano and Bond (1991) two-step system GMM estimation model to address endogeneity by following Roodman (2009). Table 3 provides a two-step GMM dynamic panel-data estimation of the factors that affect SMVOL in the United Kingdom from 2012 to 2021. The dependent variable is SMVOL, and the independent variables are CCRISK, environmental (ESCORE), social (SSCROE), and governance (GSCORE) scores from ESG, and control variables such as firm size, TQR, ROA, PM, and R&D. Table 3 exhibits direct relationships across columns 1 to 4. In column 1, we observe the direct association between CCRISK, ESG and SMVOL. Moving to column 2, we found a direct connection between CCRISK, E score and SMVOL. Column 3 shows the direct association between CCRISK, S score, and SMVOL. In column 4, we identify the direct link between CCRISK, G score and SMVOL.

In all four models, the coefficient of CCRISK exhibits a consistent and robust pattern, demonstrating statistical significance at the 1% level. The significant positive relationship between CCRISK and SMVOL is consistent with the expectation that companies exposed to higher CCRISK tend to experience greater SMVOL, hence providing support to our **Hypothesis 1**. This empirical finding aligns with the study of Noh and Park (2023), which also supports the positive association between CCRISK and SMVOL. The positive relationship between CCRISK and SMVOL can be attributed to various mechanisms, e.g., market perception, regulatory changes, physical and transition risks, investor behaviour, information asymmetry, supply chain disruptions, and the contrast between long-term climate risks and short-term market dynamics. These factors collectively contribute to the observed positive correlation between CCRISK and SMVOL, as supported by the existing literature.

The coefficient of ESG is negative and statistically significant at the 1% level. This means that an increase in ESG score is associated with a decrease in SMVOL. This suggests that firms with higher ESG scores tend to have lower SMVOL, hence supporting our **Hypothesis 2**. The negative relationship between ESG scores and SMVOL can be attributed to risk management practices, stakeholder trust, long-term orientation, reduced regulatory risks, cost efficiencies, investor preferences, resilience to external shocks, transparency, and competitive advantages associated with ESG-focused firms. These factors collectively contribute to the observed negative correlation between ESG scores and SMVOL, as supported by our statistical analysis.

In column 2, the coefficient of ESCORE is positive and statistically significant at the 5% level. This means that an increase in E score is associated with an increase in SMVOL. This suggests that firms with higher E scores tend to have higher SMVOL. In column 3, the coefficient of SSCORE is negative and statistically significant at the 1% level. This means that an increase in S score is associated with a decrease in SMVOL. In column 4, the coefficient of GSCORE is negative and statistically significant at the 1% level. This means that an increase in G score is associated with a decrease in SMVOL.

4.5. Moderating relationship analysis with GMM

Table 3 also exhibits moderating relationships across columns 5 to 8. Column 5 shows the moderating relationship of ESG between the CCRISK and SMVOL, column 6 moderating relationship of E score (ESCORE) between the CCRISK and SMVOL, Column 7 the moderating relationship of S score (SSCORE) between the CCRISK and SMVOL. In column 8, the G score (GSCORE) moderates the relationship between the CCRISK and SMVOL.

In column 5, the coefficient of the interaction term (ESG*CCRISK) is negative and statistically significant at the 1% level, indicating that the relationship between CCRISK and SMVOL is moderated by ESG, hence providing support to our **Hypothesis 3**. Specifically, the positive

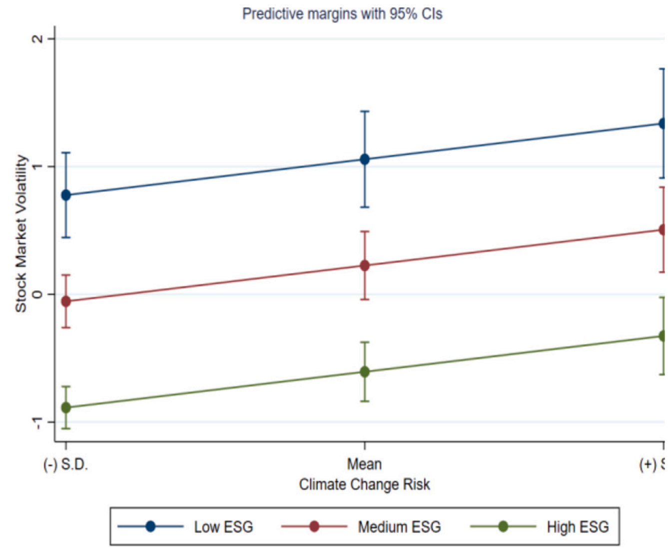

Fig. 5. ESG moderation.

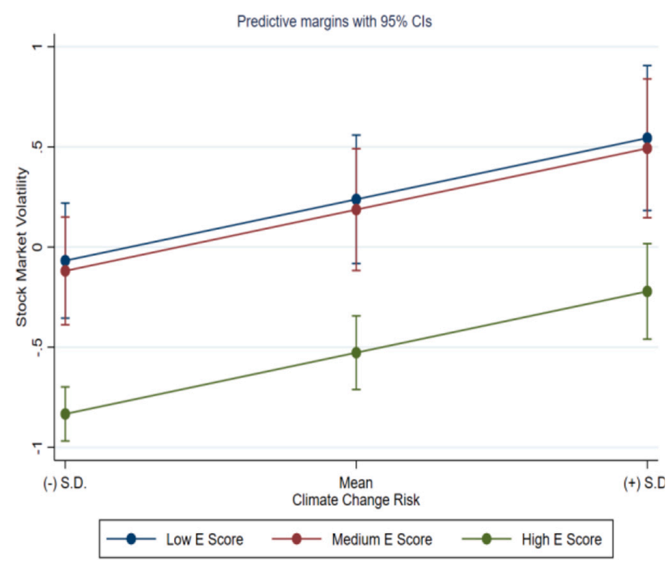

Fig. 6. E Score moderation.

relationship between CCRISK and SMVOL is stronger for firms with lower ESG scores. This suggests that firms with lower ESG scores are more likely to be affected by climate change-related events, which can lead to financial losses and disruptions to their businesses. This also implies that firms with high ESG scores may partially offset the positive impact of CCRISK on SMVOL. Firms with strong ESG practices may be better equipped to mitigate and manage CCRISK effectively. Their proactive approach to sustainability and risk management can dampen the volatility-inducing effects of climate risk. While empirical studies on this specific interaction may be limited, existing research on the individual impact of ESG and CCRISK supports the idea that strong ESG practices can mitigate the volatility associated with climate risks.

From columns 6–8, the coefficient of interaction terms represents the combined effects of CCRISK with each ESG dimension (ESCORE, SSCORE, GSCORE) on SMVOL. In column 6, the coefficient of interaction term (ESCORE*CCRISK) is positive and statistically significant at the 1% level. This means that the relationship between CCRISK and SMVOL is moderated by ESCORE. In column 7, the coefficient of interaction term (SSCORE*CCRISK) is positive and statistically significant at the 1% level. This means that the relationship between CCRISK and

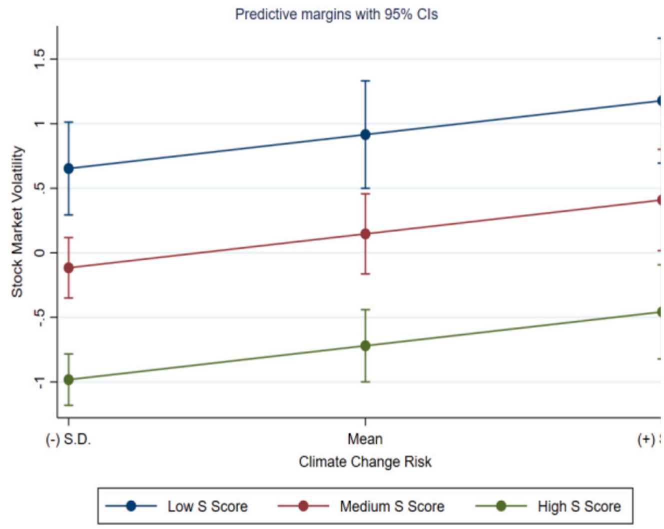

Fig. 7. S Score moderation.

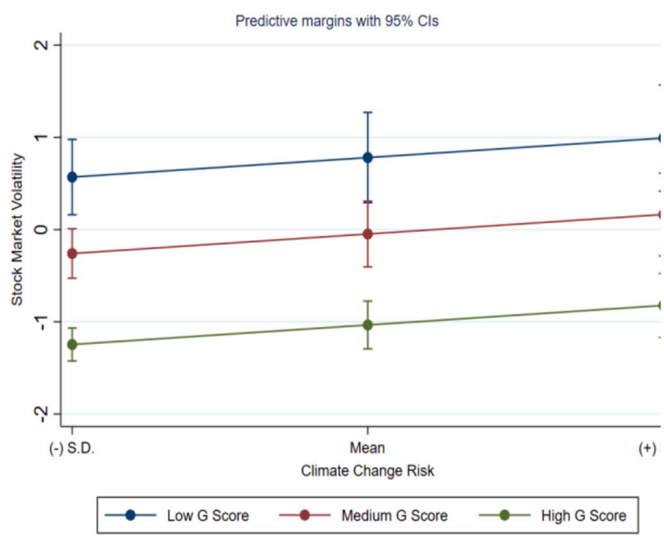

Fig. 8. G Score moderation.
Note: The X-axis shows the values of CCRISK, and the Y-axis measures the marginal effect of CCRISK on SMVOL. There are three lines representing low, medium, and high values of the moderator (ESG).

SMVOL is moderated by SSCORE. In column 8, the coefficient of interaction term (GSCORE*CCRISK) is positive and statistically significant at the 1% level. This means that the relationship between CCRISK and SMVOL is moderated by GSCORE.

In summary, Table 3 provides evidence of the relationships between CCRISK, ESG factors (ESG, ESCORE, SSCORE, GSCORE), and SMVOL. These relationships are supported by both theoretical arguments and empirical research in sustainable finance, highlighting the importance of ESG practices in mitigating the volatility introduced by CCRISK. The negative interaction effects further emphasise the combined impact of CCRISK and strong ESG practices in reducing SMVOL.

4.6. Decomposition of ESG and CCRISK-SMVOL relationship

Using standard deviations from the mean for categorisation, the moderation analysis conducted with the margin function proves to be a robust and informative approach. This method allows us to explore how the moderating variable, whether it is ESG or its individual dimensions, influences the relationship between CCRISK and SMVOL under various conditions. We categorise low and high levels based on data-driven criteria and employ the margin function to estimate and visualise SMVOL predictions while controlling for other factors. This approach offers a valid and insightful means of understanding the impact of ESG on the CCRISK-SMVOL relationship. Figs. 5–8 show the marginal effects plots visualising the moderating impact of ESG and its components on the relationship between CCRISK and SMVOL. The X-axis shows the values of CCRISK, and the Y-axis measures the marginal effect of CCRISK on SMVOL. There are three lines representing low, medium, and high values of the moderator (ESG).

In Fig. 5, the low ESG line has the steepest positive slope, indicating higher marginal effects of CCRISK on SMVOL; as ESG increases to medium and high levels, the slopes become flatter. This shows the positive impact of CCRISK on SMVOL reduces as ESG increases. It visually confirms ESG's moderating effect - dampening the CCRISK-SMVOL relationship. Fig. 6, margin plot suggests that the E score from ESG moderates the relationship between CCRISK and stock volatility. Specifically, the effect of CCRISK on SMVOL is weaker for companies with high E scores than for companies with low E scores. This means that companies with high environmental scores are less likely to experience higher SMVOL in response to CCRISK than companies with low environmental scores. In Fig. 7, companies with low S scores are less likely to experience higher SMVOL in response to CCRISK than companies with high S scores. Fig. 8 suggests that the G score of ESG moderates the relationship between CCRISK and SMVOL. Specifically, the effect of CCRISK on SMVOL is weaker for companies with high G scores than for companies with low G scores. Conversely, companies with low G scores are more likely to be exposed to CCRISK.

In summary, Figs. 5–8 show the marginal effects plots visualising the moderating impact of ESG and its components on the relationship between CCRISK and SMVOL. The visualisations clearly show the moderating effect, with flatter CCRISK-SMVOL slopes at higher levels of ESG and its components. In all cases, the higher CCRISK is associated with increased SMVOL, but this positive relationship weakens at higher levels of ESG and its components, illustrating ESG's risk-mitigating role in the face of climate change exposure.

4.7. Discussion

Our study identifies complex mechanisms linking CCRISK and SMVOL. The consistent positive correlation between CCRISK and SMVOL aligns with expectations, resonating with the tenets of the MBV theory. This framework posits that market participants adeptly integrate diverse information, including climate-related risks, into stock prices. Regulatory shifts, notably those influenced by international agreements such as the Paris Agreement, introduce uncertainties, impacting firms disparately. Recognising information asymmetry and supply chain disruptions as catalysts for varied reactions contributes to a nuanced understanding of the intricate CCRISK-SMVOL relationship.

Our findings harmonise with Stakeholder Theory, affirming that companies embracing ESG practices cultivate stakeholder trust, resilience, and long-term perspectives. Complementing this perspective, the RBV theory suggests that firms endowed with superior resources, including robust ESG practices, gain a sustainable competitive advantage, translating into diminished SMVOL.

Emphasising the pivotal role of ESG practices in risk reduction and market stability, firms with elevated ESG scores demonstrate lower SMVOL. ESG-focused companies engender stakeholder trust, enriching stability and resilience. Their long-term orientation shields them from the caprices of short-term market fluctuations, contributing to overall market stability. Moreover, ESG practices foster cost efficiencies and amplify transparency, positively shaping investor perceptions and reducing the likelihood of abrupt stock price movements.

The Marginal Effects Analysis, rooted in the Risk Management Theory, unveils how firms strategically categorise and manage climate change-related risks through ESG practices. Lower ESG scores intensify the positive association between CCRISK and SMVOL, signifying heightened vulnerability to climate-related events. Contrarily, firms with robust ESG practices partially offset the positive impact of CCRISK on SMVOL, demonstrating the risk-mitigating potential inherent in strong ESG practices.

In summary, our study propels comprehensive insights into the complex nexus of CCRISK, ESG practices, and SMVOL. This nuanced understanding is imperative for investors, policymakers, and companies navigating the dynamic landscape of sustainable finance, underscoring the potential for high-impact contributions to financial literature.

4.8. Robustness analysis

In order to ensure the robustness and reliability of our findings, we conducted a series of supplementary analyses using alternative estimation techniques and measures. The results of the robustness analysis are shown in Table 4. These robustness checks provide additional support for the validity of our main results.

4.8.1. Alternative estimation techniques

We employed Panel-Corrected Standard Errors (PCSE) in addition to our primary OLS estimation. The results consistently reaffirmed the patterns observed in our primary analysis, strengthening the credibility of our findings.

4.8.2. Alternative measures

To further validate our conclusions, we substituted the CCRISK with an alternative measure known as climate change exposure score (CCEXPO), sourced from Sautner et al. (2023a). In place of the combined ESG score, we utilised a combined Environmental and Social (E&S) score. The application of the GMM, consistent with our primary analysis, yielded results that aligned with our main findings, underscoring their stability and robustness.

4.8.3. Alternative interaction terms

In our pursuit of comprehensive analysis, we explored alternative interaction terms, specifically (CCEXPO*ESG) and (E&S*CCRISK). These additional examinations allowed us to investigate potential variations in the moderating effects of ESG and its dimensions on the CCRISK and SMVOL relationship. Our findings in this regard complemented our primary results, further consolidating the role of ESG in moderating the CCRISK-SMVOL relationship.

Together, these robustness analyses provide compelling evidence of the consistency and reliability of our research findings. They confirm the significance of ESG and its dimensions in shaping the relationship between CCRISK and SMVOL, strengthening the validity of our main conclusions.

5. Conclusion and implications

This research has delved into these intricacies by investigating the complex interplay between CCRISK, ESG factors, and SMVOL within the context of the United Kingdom. Leveraging annual firm-level data spanning the years 2012 to 2021, we employed a rigorous analytical approach encompassing OLS and GMM regressions, effectively addressing endogeneity concerns while accounting for both time series and cross-sectional dependencies. Our findings have unveiled a series of pivotal insights.

Firstly, we have established a robust and statistically significant correlation between CCRISK and SMVOL, highlighting that firms characterised by elevated CCRISK levels tend to exhibit heightened SMVOL. Secondly, our research has demonstrated a compelling negative and statistically significant connection between ESG scores and SMVOL. This implies that companies with more substantial ESG scores tend to experience lower levels of SMVOL, underscoring the potential benefits of responsible and sustainable business practices. Moreover, we have introduced a nuanced moderation analysis, which has delved into how specific dimensions of ESG can influence the CCRISK-SMVOL relationship. Our results have unveiled intricate interactions, emphasising that distinct ESG dimensions exert varying degrees of influence on this relationship. The results reinforce the importance of integrating sustainability factors into financial decision-making, not only as a means of addressing environmental and societal challenges but also as a strategy for mitigating SMVOL.

The implications of the findings from this research paper are manifold and extend to various stakeholders, including academia, investors, policymakers, corporations, and the broader financial community. These implications shed light on the significance of CCRISK and ESG considerations in the context of SMVOL.

Investors should consider the impact of CCRISK and ESG factors when formulating their investment strategies. The negative relationship between ESG scores and SMVOL suggests that incorporating sustainability criteria into investment decisions can potentially lead to more stable portfolios. Sustainable investments may offer risk mitigation benefits, making them an attractive option for risk-averse investors. Corporations need to recognise the potential consequences of CCRISK on their stock market performance. The positive relationship between CCRISK and SMVOL underscores the importance of proactive risk management strategies. Companies should assess their climate risk exposure, implement mitigation measures, and enhance transparency through ESG disclosures to maintain investor confidence.

Policymakers have a role to play in incentivising sustainable practices and climate risk mitigation. The research highlights the systemic risks associated with climate change, emphasising the need for regulatory frameworks that encourage responsible corporate behaviour. Climate-related disclosure requirements and incentives for ESG integration can contribute to more resilient financial markets. The moderation analysis reveals the nuanced influence of ESG dimensions on the CCRISK-SMVOL relationship. Corporations should recognise that not all ESG factors are equally impactful. Focusing on environmental and governance aspects may be particularly effective in reducing SMVOL. This insight can inform corporate ESG strategies.

While our study provides valuable insights into the interconnections among CCRISK, ESG practices, and SMVOL within the United Kingdom market, it is crucial to acknowledge certain limitations that may impact the generalizability of our findings: Our study, focused on the United Kingdom market, presents insightful findings that must be interpreted within the context of certain limitations. The geographical scope restricts the generalisability of our results to other global markets, each with its unique economic, regulatory, and cultural dynamics. Additionally, the distinct characteristics of the UK market, coupled with the specific timeframe of our analysis (2012-2021), may limit the broader applicability of our insights. Data disparities across markets and industries, as well as potential biases due to data comparability, should be considered. Future research, encompassing diverse markets and industry-specific nuances, is essential for a more comprehensive understanding of the relationships explored in this study.

Our study has opened avenues for future research that can deepen our understanding of the intricate relationship between CCRISK, ESG practices, and SMVOL. To enhance the breadth and applicability of our findings, we propose several avenues for future investigation:

Exploring the impact of specific events, such as the Paris Agreement, as mechanisms influencing the linkages between CCRISK and SMVOL. Investigating how regulatory and international agreements shape market perceptions and responses, providing valuable insights into the role of global events in financial market dynamics. Extending the scope of the inquiry beyond the UK market. A cross-country comparative study can unravel the nuances of climate change risk and sustainability practices in stock market volatility across diverse economic and regulatory landscapes. Comparisons between developed and emerging markets can offer a more comprehensive understanding of the global implications. Conducting a temporal analysis to observe how the relationship between

CCRISK, ESG practices, and SMVOL evolves over different time periods. This longitudinal approach can capture the dynamic nature of market responses to changing environmental and social considerations. Delve into sector-specific analyses to discern how CCRISK and ESG practices impact stock market volatility within distinct industries. Industries with varying exposure to environmental and social factors may exhibit unique patterns that merit specialised attention.

By pursuing these future research directions, scholars can contribute to a more nuanced and globally applicable understanding of the interplay between climate-related risks, sustainability practices, and stock market dynamics.

Data availability

No

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