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RESEARCH

Sovereign bond spreads and climate risk: An empirical analysis in the Euro area

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Abstract
This paper examines whether climate-related factors help explain 10-year sovereign bond spreads in the Euro Area. Unlike previous studies, we employ a novel and comprehensive set of climate indicators capturing both transition and physical climate risks. Using a panel regression with a residual-based approach, we find that climate risk is priced in Euro Area sovereign bond markets, although meaningful cross-country differences remain. In particular, the unexplained component of sovereign spreads appears to react more strongly to forward-looking indicators of carbon dependence and structural climate fragility than to mitigating factors such as institutional preparedness. Overall, financial markets reward credible climate performance and penalize delayed or insufficient transition efforts. Robustness checks and controls for cross-sectional dependence confirm the reliability of our findings.

Keywords Climate risk · Sovereign bond spreads · Climate variables · Panel analysis

JEL Classification C23 · E30 · E43 · F41 · G15 · H60 · Q56

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1 Introduction

The effects of climate change are rising. As highlighted by the European Environment Agency in a report titled *European Climate Risk Assessment* (EEA Report 01/2024)[1], human activities have led to unprecedented global warming. The average global temperature in the 12-month period between February 2023 and January 2024 exceeded preindustrial levels by 1.5°C. The year 2023 was the warmest year recorded in more than 100,000 years worldwide, at 1.48°C above preindustrial levels, and the world's ocean temperature also reached new heights. In 2023, the global temperature anomaly for Earth's land and ocean surfaces was 1.17°C higher than the average of the 20th century. The warming on the European continent was about twice the global rate, causing climate-related extreme events or mass disasters[2].

In 2021, intense rainfall led to massive flooding in Germany and Belgium, causing more than EUR 44 billion in damages and more than 200 deaths. The floods had a major impact on communities, infrastructure, agriculture, and public health. The economic and fiscal effects were significant, testing the limits of the EU Solidarity Fund. In 2023, severe flooding hit Slovenia, causing damages equivalent to approximately 16% of national GDP, highlighting the economic vulnerability of smaller nations. Moreover, Greece experienced flooding that devastated the primary agricultural region, severely impacting food production and causing extensive economic damage. In May 2023, Emilia-Romagna, a region in Italy, experienced six months' of rain in 20 days. This led to floods and landslides, which caused 17 deaths and displaced approximately 36,600 people (Emilia-Romagna news, May 2023, CEMS bulletin n.166). More than 600 roads were closed, railway tracks, buildings, and agricultural fields were damaged, riverbanks flooded, and the sewage systems were overwhelmed. According to regional government sources (in a notice dated June 15, 2023), the estimated damages amount to 8.8 billion euros.

The increasing frequency and intensity of these phenomena were the focus of a study conducted by Hale (2024) which analyzed a subset of climate-related natural disasters from the EM-DAT database and concluded that the occurrence of such disasters in most countries can be modeled using a Poisson distribution: these phenomena are no longer random and unpredictable, but instead follow a clear evolutionary pattern.

Therefore, climate change presents a risk to human life, economic activity, and consequently to the economic system. Climate risk can be categorized into physical and transition risks. Physical risk refers to the (increasing) likelihood of extreme climate-related events. Transition risk is related to how quickly and effectively an organization adapts to both internal and external changes aimed at reducing greenhouse gas emissions (GHG) and shifting to renewable energy. This transition encompasses political, legal, technological, and market changes necessary for assessing and adapting to climate change. Policy makers play a crucial role in two ways: first, to mitigate

[1] See: https://www.eea.europa.eu/publications/european-climate-risk-assessment

[2] EM-DAT defines mass disaster a situation or event which overwhelms local capacity, necessitating a request to the national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction, and human suffering.

the effects of climate change; second, to adapt government policies so as to anticipate the adverse effects of climate change and to implement appropriate measures to prevent or minimize potential damages, or to seize opportunities that may arise. Both strategies put pressure on the fiscal system, yet mitigation focuses on eliminating the root causes of climate change.

Climate change poses a threat to government solvency and financial sustainability in two key ways. First, extreme climate events destroy infrastructure and human capital, reducing income, consumption, and savings, thereby altering the growth trajectories of GDP. Second, governments must allocate significant financial resources, not only to stimulate economic growth but also to implement mitigation and adaptation strategies. Although such policies are considered a “good" use of debt, failing to take adequate action can lead investors to demand higher interest rates as a risk premium, further straining public finances. In particular, Kumar and Baldacci (2010) describe this phenomenon as a vicious cycle of climate risk and debt, as well Zenios (2024) provides a comprehensive review of the empirical methods used to assess the effects of climate risk on sovereign debt, highlighting a unanimous consensus: climate risks increase borrowing costs, making debt servicing more challenging.

Simultaneously, climate-related damages reduce fiscal space, making it harder for governments, especially those in low-income countries, to secure financing for essential mitigation and adaptation policies. This results in a doom loop in which financial instability exacerbates climate vulnerability and vice versa.

The aim of this paper is to analyze how climate risk affects financial stability by driving up interest rates on sovereign bonds, thus increasing a country’s risk of default. Although the literature on this topic is evolving, most studies suggest that developing countries are more exposed to these risks, whereas the impact of climate indicators appears less pronounced for advanced economies. This paper focuses exclusively on Euro Area countries and contributes to the existing literature by employing a novel set of climate exposure indicators, allowing for a more nuanced assessment of how environmental risks translate into sovereign credit risk within advanced economies.

In particular, we investigate to what extent different dimensions of climate risk affect sovereign bond yields in Euro Area countries. Framing the analysis in this way enables us to unravel how investors price distinct climate-related indicators and to offer a more granular perspective on the climate-sovereign risk nexus.

The paper is organized as follows. In Section 2, we review the literature on sovereign bond spreads and climate risks, highlighting existing gaps. Section 3 presents a theoretical framework, explaining how and whether investors price climate risk in sovereign bond spreads and introduces the classification of climate risk variables used in the empirical analysis. Section 4 describes the data and presents the descriptive statistics. Section 5 outlines the econometric methodology used to assess the relationship between sovereign bond spreads and climate risk variables. Section 6 reports the empirical results and robustness checks. The final section concludes.

2 Literature review and literature gaps

In recent years, the economic literature has increasingly examined the link between sovereign risk and climate change, recognizing that adaptation and mitigation policies significantly impact a country's financial stability.

The financial implications of climate risks are grounded in solid theoretical foundations. Generally, the literature is divided between models that focus on physical risks (e.g., Mallucci, 2022; Phan and Schwartzman, 2024) and those emphasizing transition risks (e.g., Carattini et al., 2023; Seghini and Dees, 2024). However, only a limited number of studies explicitly integrate both physical and transition risks within a unified theoretical framework.

On the one hand, focusing on physical risk, Mallucci (2022) extends a standard sovereign default framework to incorporate disaster risk, calibrating his model to seven Caribbean countries frequently affected by hurricanes. The results highlight that physical climate risks, such as hurricanes, reduce governments' ability to issue debt and negatively affect social welfare. Similarly, Phan and Schwartzman (2024) develop a model embedding an endogenous propagation mechanism of climate risk: capital destruction caused by disasters raises sovereign default risk and widens interest rate spreads, which in turn reduces borrowing and depresses future output and investment. Their calibration, based on catastrophe bonds, suggests that countries highly exposed to extreme weather face elevated borrowing costs and an increased likelihood of sovereign debt crises.

On the other hand, studies focusing on transition risks explore the economic consequences of policy and market shifts aimed at reducing greenhouse gas emissions. Carattini et al. (2023) employ a Dynamic Stochastic General Equilibrium model integrating pollution externalities and financial sector frictions to simulate the effects of carbon taxation in different macro prudential policy scenarios. Their findings show that while macro prudential policies can mitigate recession risks during the climate policy transition and promote growth post-transition, they cannot alone address the underlying climate externality in the absence of comprehensive climate policies. Complementing this, Seghini and Dees (2024) propose a neoclassical macroeconomic model that combines green transition policies, public debt dynamics, and macroeconomic variables. Their analysis reveals a paradox whereby necessary transition policies may exacerbate public debt burdens, raising concerns about debt sustainability and financing costs–especially in highly indebted countries. They further highlight spillover effects, where increased public debt risk deteriorates private sector financing conditions, amplifying macroeconomic challenges. A key insight is the critical role of initial debt levels, as countries with high debt are more vulnerable to the fiscal consequences of transition policies.

From an empirical perspective, most studies analyze the relationship between sovereign risk, typically proxied by sovereign bond spreads or CDS premiums, and climate risk indicators, using panel econometric techniques while controlling for macroeconomic fundamentals. Empirical studies have concentrated predominantly on the financial implications of climate risk exposure, with a particular emphasis on transition-related factors (Kling et al. 2025; Cevik and Jalles 2022; Capelle-Blancard et al. 2019; Crifo et al. 2017; Hübel 2022; Naifar 2023; Collender et al. 2023), while few studies investigate the financial implications of physical risk (Boehm 2022; Klusak et al. 2023) or of both types of climate risk (Beirne et al. 2021; Boitan and Marchewka-Bartkowiak 2022).

Several studies use the Notre Dame Global Adaptation Initiative (ND-GAIN) indicators of vulnerability and readiness as proxies for countries' structural exposure and adaptive capacity to climate change (Kling et al. 2025; Cevik and Jalles 2022; Beirne et al. 2021; Naifar 2023). These measures are often interpreted as hybrid indicators as they combine elements of physical risk with the ability of governments and institutions to manage the transition and attract climate-related investment. One of the first contributions in this stream of literature is the study of Kling et al. (2025). Using panel least squares and fixed effects models, the authors demonstrate that climate vulnerability raises government bond yields, while greater readiness (i.e. adaptive capacity) lowers them. Building on this, Cevik and Jalles (2022) find similar results using a broader sample and more advanced econometric tools, such as the Generalized Method of Moments, highlighting that countries, especially developing ones, with greater vulnerability pay higher risk premia on sovereign bonds. Innovatively, Beirne et al. (2021) apply a structural panel VAR approach to identify shocks to climate vulnerability and resilience across 40 countries, analyzing both transition and physical risk, including advanced and emerging economies. Their findings confirm that climate risk significantly affects borrowing costs, with increased vulnerability raising sovereign spreads and greater resilience dampening them. In addition, Naifar (2023) employs a panel quantile regression framework and finds that climate readiness significantly reduces CDS spreads, whereas climate vulnerability increases them (with the exception of the upper tail). Moreover, the mitigating effect of readiness is strongest at higher quantiles.

Additional measures of transition risk have been adopted in the literature. For example, Collender et al. (2023), using panel least squares and fixed effects models, show that greenhouse gas emissions, used as a proxy of climate risk exposure, significantly affect sovereign yields and spreads, with countries exhibiting lower emissions facing lower borrowing costs, and also find that, among advanced economies, higher renewable energy consumption and reduced dependence on natural resource rents are associated with lower sovereign financing costs. Other studies have used alternative indicators based on ESG. Capelle-Blancard et al. (2019) construct a composite ESG index using World Bank data and principal component analysis, finding that stronger ESG performance reduces sovereign spreads, particularly in countries of the euro area. Crifo et al. (2017), using the Vigeo sustainability rating database, confirm these results. Hübel (2022) analyzes 1-year CDS spreads instead of bond yields and finds a significant negative relationship between ESG scores and sovereign credit risk, suggesting that markets price the mitigating effect of strong ESG performance.

Focusing specifically on Europe, Boitan and Marchewka-Bartkowiak (2022) use the Climate Change Performance Index as a measure of transition risk and the Climate Risk Index as a measure of physical risk developed by the GermanWatch Institute. By incorporating regional dummy variables reflecting EU bio-geographical zones, they find that countries in the Mediterranean region, which are more vulnerable to climate change, face higher sovereign risk premia than those in the Atlantic zone.

In contrast to this body of work on transition risk, relatively few empirical studies directly address physical climate risk. Notably, Boehm (2022) offers an innovative analysis by regressing returns of the Emerging Market Bond Index on temperature anomalies. Using OLS regressions with country, time, and regional fixed effects, the study shows that countries experiencing greater temperature deviations (particularly those already warmer on average and with weaker institutions) exhibit worse sovereign bond performance. These findings highlight the increasing role of institutional quality in mediating the impact of climate shocks on financial stability.

Klusak et al. (2023), meanwhile, focus on long-term creditworthiness by developing the first climate-adjusted sovereign credit rating model. Based on S&P data, their results suggest that in the absence of strong mitigation policies, more than 60 sovereigns could face climate-induced downgrades by 2030, with estimated increases in annual interest payments ranging from \$137 to \$205 billion. In particular, their simulations emphasize the potential of full adherence to the Paris Agreement to neutralize these adverse effects.

In summary, the empirical literature provides compelling evidence that both transition and physical climate risks influence sovereign credit risk due to the rising cost of debt. However, most studies focus on transition indicators, with relatively few analyses capturing the effects of physical risks or both. Moreover, many studies investigate advanced and/or developing countries, with a few studies focusing on the European context. In addition, many papers use indicators rather than being explicitly targeted at climate-related risk. For example, using ESG scores as a proxy for transition risk (Capelle-Blancard et al. 2019; Hübel 2022) may not be fully appropriate: ESG indicators encompass environmental, social, and governance dimensions, which are not only related to environmental risks. In this sense, using a composite ESG score rather than the isolated environmental (E) score is more permissive, while focusing solely on the E component would provide a stricter and more targeted measure of climate-related risk.

Moreover, empirical literature tends to overlook the presence of cross-sectional dependence (CD) in panel data models (e.g., Kling et al., 2025; Capelle-Blancard et al., 2019). This issue is particularly relevant when analyzing groups of units that are strongly interconnected, such as countries that share geographical proximity, economic agreements, or common policy frameworks. CD arises when cross-sectional units (countries, companies, individuals) are not independent but are instead influenced by common shocks or spillover effects. If we denote with u_{it} the error term of a linear panel regression model, CD occurs when $\mathbb{E}(u_{it}u_{jt}) = \mathrm{cov}(u_{it}, u_{jt}) \neq 0$ for some t and some $i \neq j$, where $i = 1, \ldots, j \ldots, N$ represents the cross-sectional dimension and $t = 1, \ldots, T$ the time dimension. This issue is particularly relevant when analyzing groups of units that are strongly interconnected, such as countries that share geographical proximity, economic agreements, or common policy frameworks[3].

This paper contributes to the existing literature in several ways. First, we jointly examine the role of both transition and physical climate risks in explaining sovereign

[3] Two types of CD can be distinguished: weak and strong dependence. See Sarafidis and Wansbeek (2012) for a detailed discussion.

risk. Second, we employ a novel and rich set of climate-related variables that have received limited attention in prior empirical studies. Third, we narrow the analysis to a panel of Euro Area countries, enabling a more granular assessment within an economically and institutionally integrated area. Finally, we address key methodological concerns by implementing multiple robustness checks and explicitly testing for the presence of cross-sectional dependence in the panel structure.

3 A theoretical framework for climate-related indicators

Assessing the effects of climate change on public finances is inherently challenging for several reasons. A straightforward approach would be to examine the dynamics of the debt-to-GDP ratio, thereby capturing the potential vicious circle between climate change and sovereign risk.[4] However, this strategy presents well-known empirical difficulties due to the endogeneity between debt accumulation and GDP growth (see Panizza and Presbitero, 2014), the key variable that shapes investors' perceptions of fiscal sustainability.

For this reason, the literature has increasingly focused on sovereign bond yields, typically at 10-year maturity, as the main empirical object of analysis. Long-term yields embed investors' expectations about future short-term rates, default risk, and risk premia, and therefore provide a forward-looking measure of the perceived cost of sovereign financing. In this sense, yields are a more tractable and informative metric to investigate how climate-related risks and policies are priced into sovereign debt markets. Schematically, the bond yield $y^{(T)}$ for maturity T could be expressed as a function $\mathscr{F}(\cdot)$ of a set of variables:

$$y_t^{(T)} = \mathscr{F}\Big(\mathbb{E}_t[r_{t+j}],\, \mathbb{E}_t[\pi_{t+j}],\, \mathbb{E}_t[f(Macro_{t+j}, RP_{t+j}, CC_{t+j})]\Big) \tag{1}$$

where $\mathbb{E}_t[r_{t+j}]$ denotes investors' expectations of current and future short-term interest rates, and $\mathbb{E}_t[\pi_{t+j}]$ captures both current and expected inflation, the term $\mathbb{E}_t[f(Macro_{t+j}, RP_{t+j}, CC_{t+j})]$ summarizes investors' expectations about current and future evolution of fiscal and macroeconomic fundamentals (*Macro*), sovereign risk premia (*RP*), and climate-related indicators (*CC*), where $j = 0, ..., T$. In a simplified setting, it is useful to combine *Macro*, *RP*, and *CC* into a single function $f(\cdot)$[5]. In our hypothesis, climate variables influence both expected fundamentals and risk premia, thereby affecting the level of long-term yields. The above relation highlights that macroeconomic fundamentals, risk premia and climate-related factors are not independent channels but interdependent arguments of the same function $\mathscr{F}(\cdot)$. Thus, climate risks may alter macroeconomic conditions (growth or debt dynamics),

[4] Countries that already struggle with high debt burdens tend to be more vulnerable to the adverse impacts of climate change; conversely, climate change exacerbates debt vulnerabilities. This feedback loop is particularly problematic as it reinforces fiscal fragility and weakens sovereign solvency.

[5] In our framework, we abstract from the potential effects of climate change on inflation dynamics. However, a growing strand of research investigates the role of central banks in managing the interplay between climate risks, inflation and monetary policy (Qi et al. 2025; Shears et al. 2025; Cevik and Jalles 2024).

affect the level and volatility of risk premia, and feed back into fiscal fundamentals. Moreover, climate risks may operate through channels that unfold over different time horizons. Some effects are relatively immediate: climate-related disasters (such as extreme weather events) or policy interventions intended to alter economic fundamentals (for example, green subsidies, carbon taxes or plastic levies) may increase fiscal pressure or heighten uncertainty, thereby putting upward pressure on sovereign spreads in the short term. Other effects materialize gradually: investors form expectations about a country's long-term alignment with climate objectives, the credibility of its transition strategy and its capacity to adapt to future climate shocks. When these expectations are favorable, climate policies, despite their potential short-term fiscal costs, can be interpreted as signals of long-term resilience and policy commitment, ultimately reducing perceived transition risks and lowering sovereign financing costs. In this sense, investors may price an immediate cost but a long-term improvement in sovereign creditworthiness.

In line with the theoretical framework described above, the climate-related indicators employed in our analysis can be grouped into three broad categories: transition risk, physical risk, and hybrid measures. Transition risk indicators capture the exposure of a country to the economic and financial consequences of the decarbonization process and policy changes. In this category, we include the LSEG Refinitiv Environmental Score (E), which proxies the environmental performance and governance quality of a country, as well as measures of carbon intensity such as CO_2 (CO2) emissions per unit of GDP and per capita greenhouse gas emissions (GHGpc). We also consider policy-based indicators such as ENvironmentally related Tax Revenue as share of GDP (ENTR), which reflects the fiscal stance on environmental taxation, and the Renewable ENergy share (REN), which measures the progress in the energy transition. Physical risk is instead captured by the European Extreme Events Climate Index (E3CI), which provides high-frequency information on the occurrence and severity of extreme weather events. This indicator is directly related to the short-term fiscal consequences of climate shocks, such as disaster relief and reconstruction costs, and to the repricing of sovereign risk premia. Finally, hybrid indicators account for both structural vulnerability and adaptive capacity. Specifically, we employ the Notre Dame Global Adaptation (ND-GAIN) Indices, the VULNerability Index (VULN), measuring exposure and sensitivity to climate risks, and the READiness Index (READ), which reflects a country's economic, institutional and social ability to implement adaptation effectively and attract climate-related investment. In Section 4, we provide a detailed description of each variable used as a proxy for climate risk.

At this stage, one point merits clarification, namely how the climate variables employed in the empirical analysis should be interpreted as proxies for climate risk. Although climate change is a global externality and unilateral reductions in CO_2 and GHG emissions cannot solve the problem of global warming by themselves, emission levels can still be informative for investors. High-emitting countries can first be perceived as failing to modernize their production technologies and energy mix, signaling weaker productivity growth over the long run. Second, they may be seen as misaligned with international climate commitments, thus facing reputational costs or sanctions (e.g., Collender et al., 2023). Third, high emissions increase the likelihood of abrupt policy adjustments (such as the introduction of carbon taxes or stricter regulations), which could require disruptive changes in the production structure. Through these channels, CO_2 and GHG indicators serve as meaningful proxies for transition risk and are relevant for the pricing of sovereign bonds. Consequently, the share of renewable energy share (REN) provides a measure of the extent to which a country has already diversified its energy mix away from fossil fuels, thereby reducing its exposure to energy price shocks and future carbon constraints. Likewise, environmentally related tax revenue as share of GDP (ENTR) reflects the use of fiscal instruments to internalize environmental externalities and to signal commitment to international climate objectives. In this sense, the E-score (E) serves as a broad, composite indicator of environmental performance and governance quality. A higher score signals stronger commitment to sustainable policies and alignment with international climate objectives, which investors may interpret as reducing long-term transition risks and sovereign credit risk. Beyond transition risk, investors are also concerned with the direct fiscal and economic consequences of climate shocks. The European Extreme Events Climate Index (E3CI) is informative in this regard, as extreme events can immediately deteriorate public finances through reconstruction costs and lower economic activity. By increasing the likelihood of fiscal slippages and higher future borrowing needs, such shocks translate into higher risk premia demanded by investors. Similarly, indicators of vulnerability and readiness of ND-GAIN are relevant because they capture the long-run structural dimension of climate risk. A high vulnerability score signals greater exposure to climate-related damages, implying larger contingent fiscal liabilities and weaker debt sustainability. In contrast, higher readiness indicates institutional and economic capacity to adapt and to credibly implement climate policies, which investors may interpret as reducing sovereign risk premia. Thus, vulnerability and readiness jointly provide information on whether climate shocks are likely to amplify sovereign risk or be effectively absorbed.

A final remark concerns a limitation of our framework, namely the potential endogeneity of some climate indicators (particularly CO_2 or GHG emissions and policy variables), since wealthier countries typically display cleaner consumption patterns while simultaneously facing lower sovereign risk. While our framework cannot fully resolve the potential endogeneity problem, we mitigate it in two ways. First, in line with Collender et al. (2023), we control for key macroeconomic fundamentals (growth, debt, inflation, fiscal balance) as well as risk factors. Second, our econometric specification includes both country and time fixed effects, thereby accounting for unobserved structural heterogeneity and common shocks that could jointly influence climate indicators and sovereign spreads. Finally, we restrict our sample to Euro Area countries, which are relatively homogeneous in terms of income levels, institutional quality, and policy frameworks. This design choice reduces the risk of strong biases that could arise in more heterogeneous panels combining advanced and emerging economies, where endogeneity concerns are likely to be more severe.

4 Data

In this section, we provide information about the dataset used in the empirical analysis in Subsection 4.1 and present the descriptive statistics in Subsection 4.2.

4.1 Dataset

We construct an unbalanced panel dataset covering 20 Euro Area countries: Austria, Belgium, Croatia, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Slovakia, Slovenia and Spain. The dataset consists of annual observations from 1995 to 2023, compiled from a combination of public and private sources. The time span is constrained by the availability of data, particularly for several key climate-related variables. We restrict the sample to Euro Area countries to ensure a homogeneous monetary policy and to avoid confounding effects arising from exchange rate fluctuations and currency risk. This choice allows us to isolate differences in sovereign risk premia that are not driven by currency mismatches, but instead by fundamentals and climate–related exposures.

Our data sources include the World Bank's World Development Indicators (WDI), the IMF's Global Debt, the OECD, Eurostat, LSEG Refinitiv, the Notre Dame Global Adaptation Index (ND-GAIN), the International Foundation Big Data and Artificial Intelligence for Human Development and the Global Macro Database of Müller et al. (2025)[6].

Table 1 provides a comprehensive list of the variables used in our empirical analysis, along with their respective sources. Our primary focus is on the 10-years sovereign bond yield spreads against the German benchmark (SPREAD). We employ several climate-related indicators, some of which are novel in existing literature. First, we utilize the E-score (E) indicator produced by LSEG Refinitiv. The variable ranges from 0 to 100, where a value closer to 100 indicates that the country is considered more "green" (with a higher environmental component), and vice versa.

Second, we use two complementary emissions-based indicators that capture different dimensions of climate exposure. On the one hand, CO_2 emissions per purchasing power parity dollar of GDP (CO2) proxy the carbon intensity of economic activity, reflecting how emission-intensive a country's production structure is. On the other hand, net greenhouse gas emissions per capita (GHGpc) capture the total emissions generated at the population level, aggregating CO_2, nitrous oxide (N_2O), methane, and other greenhouse gases. By jointly considering these measures, we can analyze climate risk both in terms of emissions intensity and aggregate per-capita emissions.

Third, we employ two proxy variables to represent the adaptive and mitigation policies implemented by policymakers: the ENvironmentally related Tax Revenue as share of GDP (ENTR) which is measured as tax revenue under energy tax bases, expressed as a percentage of GDP, and the Renewable ENergy share (REN) which represents the percentage of energy derived from renewable sources. The calculation methods are based on data collected under Regulation (EC) No. 1099/2008 on energy statistics, supplemented by additional data from national administrations to Eurostat. It should be noted that in some countries statistical systems are still developing to

[6] The Global Macro Database by Müller et al. (2025) is an open-source and continuously updated dataset that harmonizes macroeconomic statistics from 31 major contemporary sources (including the IMF, World Bank, and OECD), complemented with historical datasets. It provides annual time series for 46 macroeconomic variables across 243 countries, from the earliest available observations to projections for 2030. The database is available at: https://www.globalmacrodata.com.

Table 1 List of variables of the dataset

Label	Name	Source
SPREAD	10-year sovereign bond yields spread against the German benchmark	LSEG Refinitiv
E	Environmental score	LSEG Refinitiv
CO2	CO_2 emissions as share of GDP	Our World in Data
GHGpc	Per capita GHG emissions	Our World in Data
ENTR	Environmentally Related Tax Revenue as share of GDP	OECD
REN	Renewable Energy Share	Eurostat
VULN	Vulnerability Index	ND-GAIN
READ	Readiness Index	ND-GAIN
E3CI	European Extreme Events Climate Index	IFAB
gGDP	GDP growth rate	WDI
DEBT	Government debt as share of GDP	GMD
INFL	Inflation rate	WDI
GPB	Government Primary Balance as share of GDP	WDI
TB	Trade Balance as share of GDP	WDI
TAX	Tax revenue as share of GDP	WDI
POL	Political Stability and Absence of Violence/Terrorism index	WDI

Note: The table shows the set of variables employed in the empirical analysis, indicating their labels, definitions and data sources. WDI refers to the World Bank World Development Indicators; OECD to the Organisation for Economic Co-operation and Development database; Eurostat to the Statistical Office of the European Union; ND-GAIN to the Notre Dame Global Adaptation Initiative; IFAB to the International Foundation Big Data and Artificial Intelligence for Human Development; and GMD to the Global Macro Database of Müller et al. (2025). The data on CO_2 intensity (*Jones et al. (2024); Population based on various sources (2024) – with major processing by Our World in Data*) and per capita greenhouse gas emissions (*Global Carbon Budget (2024) and Bolt and van Zanden – Maddison Project Database 2023 – with major processing by Our World in Data*)

meet all requirements of the Renewable Energy Directive I or II, especially regarding ambient heat from heat pumps, renewable cooling, or the sustainability of solid and gaseous biofuels.

Fourth, we incorporate indicators from ND-GAIN to capture vulnerability and readiness dimensions. The Vulnerability Index (VULN) quantifies the exposure, sensitivity, and adaptive capacity of a country in six sectors: food, water, health, ecosystem services, human habitat, and infrastructure. Higher scores indicate greater vulnerability. The Readiness Index (READ) assesses the capacity to effectively leverage investments in adaptation through three sub dimensions: economic, governance, and social readiness. Both indices range from 0 to 100, with higher values indicating greater exposure or preparedness, respectively.

Finally, to account for physical climate risk, we employ the European Extreme Events Climate Index (E3CI), developed by the Joint Research Center of the European Commission[7]. The E3CI monitors the occurrence and severity of extreme climate events throughout Europe based on ERA5 atmospheric reanalysis data. The index captures anomalies in seven categories of extreme weather events and assigns values relative to historical variability; values greater than 1 indicate anomalies that exceed interannual climate variability. This indicator offers granular, high-frequency information relevant for assessing the immediate impacts of climate extremes on economic and social systems.

In addition to our main explanatory variables, we include several control variables to account for macroeconomic and financial conditions that may influence sovereign bond yields. First, we consider the GDP growth rate (gGDP) as a primary indicator of economic performance, capturing fluctuations in output over time. We also include the government DEBT-to-GDP ratio (DEBT), which reflects a country's fiscal position and overall debt sustainability. INFLation (INFL) is measured as the annual percentage change in the Consumer Price Index and is used to account for macroeconomic stability and monetary dynamics. Second, we control for the Government Primary Balance (GPB), expressed as a percentage of GDP. This measure isolates the structural fiscal balance by excluding interest payments, offering a clearer view of the government's budgetary stance. The Trade Balance as a share of GDP (TB) is included to capture the dynamics of the external sector, reflecting the position of net exports of each country. We also consider TAX revenue as a share of GDP (TAX) to represent the government's ability to generate revenue, which is essential for fiscal sustainability. Finally, to account for institutional and political stability, we include the POLitical stability and absence of violence/terrorism indicator (POL) developed by the World Bank's Worldwide Governance Indicators (WGI). This index measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism, ranging from –2.5 to +2.5. Political stability represents a key determinant of sovereign risk: strong and credible institutions reduce uncertainty over policy implementation and fiscal discipline, thus lowering the perceived probability of default. Conversely, political instability may increase sovereign risk premia by raising uncertainty and vulnerability to adverse shocks.

4.2 Descriptive analysis

Table 2 shows the descriptive statistics of the variables used in the empirical analysis. These statistics include the mean, standard deviation, minimum and maximum values for each variable, calculated overall, and decomposed into between-country (across-country averages) and within-country (over time) components. The variance within a group refers to the variability of a variable over time within a single country, while the variance between groups refers to the variability of the variable across different countries. Descriptive statistics show notable dispersion in sovereign spreads, with an average of 1.30 and a wide range from negative values to peaks above 30, reflecting the heterogeneous sovereign risk profiles within the Euro Area over the sample

[7] For more information, see: https://climateindex.eu/en/data/.

Table 2 Descriptive statistics

		Mean	Std. Dev.	Min	Max
SPREAD	overall	1.304	2.360	-3.151	32.069
	between	-	1.196	-0.011	4.854
	within	-	2.046	-3.428	28.518
E	overall	79.467	7.805	61.730	100.000
	between	-	7.347	70.658	99.221
	within	-	3.111	68.796	88.508
CO2	overall	28.901	12.712	9.408	98.689
	between	-	9.566	16.608	59.048
	within	-	8.643	-5.628	68.542
GHGpc	overall	10.309	4.781	2.092	28.040
	between	-	4.479	5.453	21.301
	within	-	1.954	0.870	17.049
ENTR	overall	2.656	0.706	0.847	5.318
	between	-	0.564	1.767	3.808
	within	-	0.444	0.909	4.165
REN	overall	18.132	11.203	0.102	50.750
	between	-	10.466	5.112	37.111
	within	-	4.634	7.423	32.362
READ	overall	54.159	9.887	34.784	79.867
	between	-	9.163	41.992	75.266
	within	-	4.251	40.835	65.120
VULN	overall	33.686	2.747	28.011	39.564
	between	-	2.739	28.452	38.160
	within	-	0.653	31.140	35.819
E3C1	overall	0.107	0.694	-0.321	14.365
	between	-	0.124	-0.044	0.565
	within	-	0.683	-0.779	13.908
gGDP	overall	2.766	4.051	-16.040	24.616
	between	-	1.363	0.790	5.987
	within	-	3.827	-16.935	21.394
DEBT	overall	61.581	41.236	0.828	249.366
	between	-	35.040	7.525	145.620
	within	-	23.013	-27.421	165.327
INFL	overall	3.031	3.781	-4.448	39.648
	between	-	1.424	1.616	5.971
	within	-	3.517	-3.700	37.082
GPB	overall	-1.076	5.677	-22.122	19.158
	between	-	3.749	-6.095	7.025
	within	-	4.344	-21.471	17.694
TB	overall	121.974	64.402	36.126	412.177
	between	-	61.224	52.645	302.992
	within	-	24.294	8.526	231.159
TAX	overall	21.700	3.374	10.189	28.423
	between	-	3.112	13.838	26.154
	within	-	1.747	15.088	27.646
POL	overall	0.787	0.412	-0.475	1.759

Table 2 (continued)

	Mean	Std. Dev.	Min	Max
between	-	0.356	0.117	1.365
within	-	0.221	0.190	1.516

Note: The table shows the descriptive statistics of variables used in the empirical analysis (average, standard deviation, minimum and maximum values). Overall, between and within refer to the decomposition of the standard deviation (Std. Dev) in panel data. The overall standard deviation is the total standard deviation; the between standard deviation captures cross-country dispersion; the within standard deviation captures time variation within each country. For the definition of the variables, see Table 1

period. Environmental performance (E) is relatively high on average (79.47), and the cross-country variation is bigger than the within country one, suggesting a strong heterogeneity in the Euro Area countries in terms of environmental performance. Similarly, CO_2 intensity and GHG emissions per capita exhibit substantial heterogeneity across countries, consistent with different industrial structures and decarbonization paths. Renewable energy shares (REN) vary considerably, ranging from less than 1% to above 50%, suggesting uneven progress in the energy transition. Vulnerability (VULN) and Readiness (READ) display meaningful cross-country differences and limited within variation. Finally, for E3CI, the within variation is bigger than the cross-country one, revealing a high dispersion of extreme events inside each country over time that is not correlated with the one in the other countries.

Fiscal and macroeconomic variables highlight marked differences in the Euro Area: debt ratios (DEBT) vary widely (1% to 249% of GDP). Trade Balance (TB), Tax revenue as share of GDP (TAX) and Political Stability and Absence of Violence/Terrorism index (POL) have a higher variance between countries than within a single country over time. On the other hand, inflation rate (INFL), GDP growth rate (gGDP) and Government Primary Balance (GPB) have a higher variance within a single country over time than between countries. Overall, the data display pronounced heterogeneity across member states more in climate-related variables than in macro-financial ones.

Table 3 shows the correlation matrix of all variables used in empirical analysis. Sovereign spreads (SPREAD) are negatively associated with environmental and institutional quality: for instance, the correlation with the environmental score (E) is -0.425, with readiness (READ) -0.322, and with political stability (POL) -0.332. Conversely, spreads increase with fiscal and climate vulnerability: the correlation with public debt (DEBT) is 0.366 and with vulnerability (VULN) is 0.225. These results suggest that stronger environmental stewardship and institutional strength are linked to lower sovereign risk, whereas fiscal fragility and climate exposure raise borrowing costs. Transition indicators exhibit internally coherent levels: renewable energy share (REN) is negatively correlated with CO_2 intensity (-0.279) and GHG emissions per capita (-0.198), while the environmental score (E) is strongly and positively correlated with GHG emissions per capita (0.603) and with readiness (0.589)). Vulnerability displays strong negative correlations with both the environmental score (-0.566) and readiness (-0.700), consistent with the intuition that more vulnerable economies tend to lag in climate preparedness.

Table 3 Correlation matrix.

	SPREAD	E	CO2	GHGpc	ENTR	REN	READ	VULN	E3CI	gGDP	DEBT	INFL	GPB	TB	TAX	POL
SPREAD	1															
E	-0.425***	1														
CO2	0.082	-0.065	1													
GHGpc	-0.222***	0.603***	0.527***	1												
ENTR	0.199***	-0.335***	0.076	-0.112*	1											
REN	0.074	-0.318***	-0.279***	-0.198***	0.180**	1										
READ	-0.322***	0.589***	-0.113*	0.542***	-0.070	0.160**	1									
VULN	0.225***	-0.566***	0.112*	-0.403***	0.176**	-0.063	-0.700***	1								
E3CI	-0.006	0.111*	-0.161**	-0.058	-0.124*	0.014	-0.012	-0.032	1							
gGDP	-0.341***	0.137*	-0.006	0.070	-0.153**	-0.101	-0.032	0.042	0.068	1						
DEBT	0.366***	-0.204***	-0.254***	-0.436***	0.237***	-0.046	-0.301***	0.036	0.059	-0.226***	1					
INFL	-0.077	-0.062	0.122*	0.002	-0.220***	0.078	-0.093	0.176**	-0.049	0.161**	-0.276***	1				
GPB	-0.057	0.412***	-0.216***	0.247***	0.161**	-0.053	0.416***	-0.305***	-0.019	-0.060	-0.037	-0.374***	1			
TB	-0.174**	0.495***	0.219***	0.498***	-0.196***	-0.391***	0.177**	-0.004	0.125*	0.296***	-0.410***	0.071	0.309***	1		
TAX	-0.003	0.317***	0.070	0.107	0.326***	-0.201***	0.223***	-0.196***	-0.088	-0.044	0.315***	-0.115*	0.205***	0.135*	1	
POL	-0.332***	0.393***	0.158**	0.542***	-0.017	-0.003	0.462***	-0.245***	-0.015	0.198***	-0.489***	-0.025	0.329***	0.548***	0.262***	1

Note: The table shows the correlation matrix between the variables used in the empirical analysis. *p-value < 0.1; **p-value < 0.05; ***p-value < 0.01. For the definition of the variables, see Table 1.

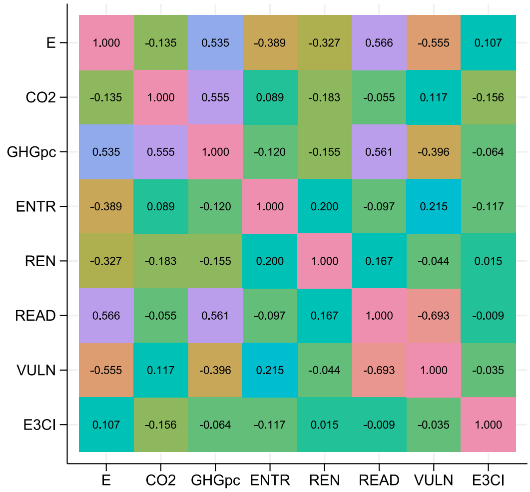
For a more focused analysis of climate variables, Fig. 1 shows the heat plot of climate indicators used in the empirical analysis. The Environmental score (E) exhibits strong positive association with per-capita greenhouse gas emissions (GHGpc) and climate-readiness (READ), and a marked negative relationship with climate vulnerability (VULN), confirming that environmentally performing countries tend to be those with stronger institutional readiness and lower vulnerability. CO2 emissions and GHGpc are positively correlated, as expected, while renewable energy share (REN) is negatively associated with both emissions and vulnerability, consistent with cleaner energy mixes being linked to more resilient and advanced transition profiles. Conversely, the E3CI index shows weak correlations with other indicators, reflecting its high-frequency physical risk nature and country-specific heterogeneity in extreme weather events. Overall, the climate variables display expected levels of correlation aligned with their conceptual definitions, while retaining sufficient independent variation to justify their joint use in empirical estimation.

Figure 2 shows the evolution of the SPREAD variable over time. Following the 2008 global financial crisis, sovereign spreads rose sharply, with a pronounced spike during the European sovereign debt crisis (2010–2012), particularly for Southern European economies. Subsequently, spreads gradually converged toward values close to zero, reflecting improved fiscal coordination, strengthened EU financial governance frameworks and unconventional monetary policies by the European Central Bank. After the Paris Agreement of 2015, we notice an evident convergence of sovereign spreads, which became more pronounced in the post-COVID period (from 2021 onward). This pattern reflects a reduction in cross-country heterogeneity in sovereign spreads among Euro Area countries.

In Fig. 3, we further decompose the SPREAD variable into its components within and between countries. The figure highlights heterogeneity among Euro zone countries: despite sharing a common currency, member states have experienced different levels and volatilities of sovereign spreads, reflecting diverse fiscal conditions, debt trajectories and market perceptions of creditworthiness. The largest and most persistent spikes are observed for Greece and, to a lesser extent, Portugal and Italy, while core countries such as Austria, Belgium, Finland and France display more contained and stable spreads. These conclusions are supported by the variance decomposition presented in Table 2, which suggests that both between-country and within-country components contribute meaningfully to the overall variability of the SPREAD. However, the between-country component appears to be slightly more influential than the within-country component, indicating that structural differences at the country level play a key role in explaining spread dynamics.

Finally, to assess the stationarity of SPREAD, we use the Im-Pesaran-Shin (IPS) unit root test, which rejects the null hypothesis of unit roots in all panels, at the 1% significance level. Therefore, at least a subset of the panels is stationary, suggesting that unit root issues are unlikely to pose concerns for the subsequent panel estimations.

Fig. 1 Heat plot of climate variables used in empirical analysis. *Note:* The figure shows the correlation matrix in heat plot format of the climate variables used in empirical analysis



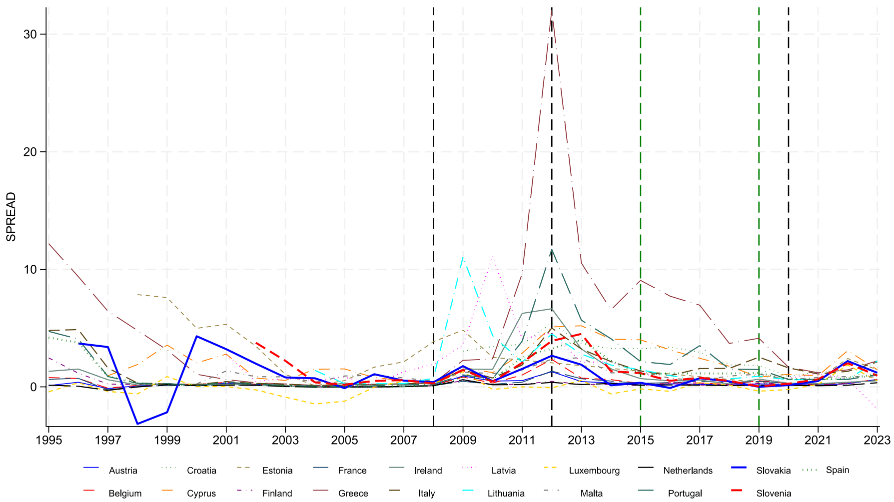


Fig. 2 10-year sovereign bond spreads against the German benchmark from 1995 to 2023. *Note:* The figure shows the evolution of 10-year sovereign bond spreads of euro-area countries relative to the German benchmark over the period 1995–2023. The vertical black lines indicate the most relevant systemic events: the Global Financial Crisis (2007–2008), the subsequent Euro Area sovereign debt crisis (2010–2012), and the COVID-19 pandemic (2020). The vertical green lines mark major climate-policy milestones, namely the Paris Agreement (2015) and the introduction of the European Green Deal (2019)

5 Methodology

In order to evaluate the relationship between 10-year sovereign bond yield spreads and a large set of climate variables, first, we estimate a dynamic linear panel regression model, in which the dependent variable is the 10-year sovereign bond yield spread relative to the German benchmark.

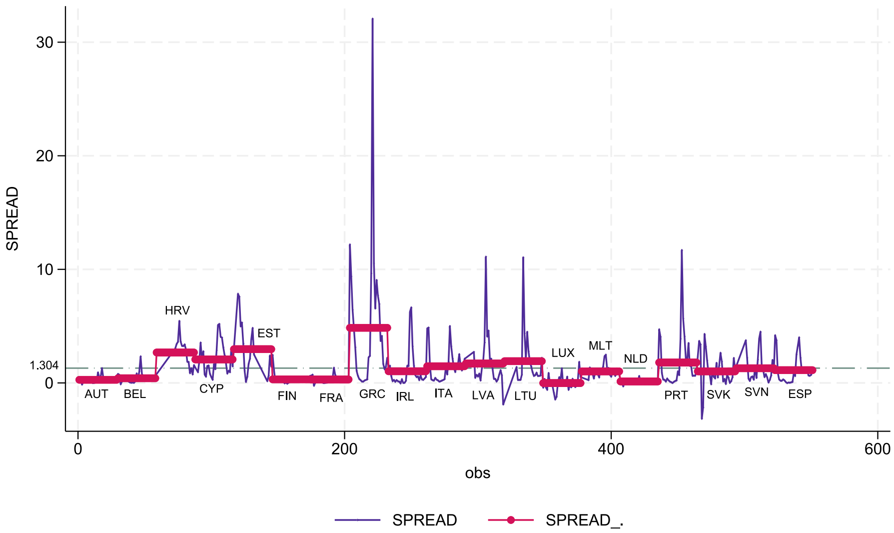


Fig. 3 Representation of country heterogeneity in the 10-year sovereign bond yield spreads against the German benchmark. *Note:* The figure shows the 10-year sovereign bond yield spreads relative to Germany, ordered by country (alphabetical order). The purple line represents the temporal evolution of the 10-year sovereign bond yield spreads, the horizontal red bars represent the country-specific average of SPREAD (denoted as SPREAD_.). The dashed gray line indicates the overall average

The dynamic panel regression model is as follows:

$$\begin{aligned} \mathrm{SPREAD}_{it} &= \alpha_i + \rho\mathrm{SPREAD}_{it-1} + \beta_1\mathrm{gGDP}_{it} + \beta_2\mathrm{DEBT}_{it} + \\ \beta_3\mathrm{INFL}_{it} &+ \beta_4\mathrm{GPB}_{it} + \beta_5\mathrm{TB}_{it} + \beta_6\mathrm{TAX}_{it} + \beta_7\mathrm{POL}_{it} + \tau_t + \varepsilon_{it} \end{aligned} \tag{2}$$

where α_i represents the individual time-invariant effects, and ε_{it} is the idiosyncratic error term, assumed to be distributed independently and identically (i.i.d.). We indicate with τ_t the time fixed effects, which are included to capture unobserved common shocks and temporal heterogeneity affecting all countries in a given year. The ρ coefficient is the autoregressive parameter. Based on the results of the IPS unit root test, we expect $|\rho| < 1$. Second, in order to assess whether climate risk variables influence the spread vis-à-vis the German benchmark, we adopt a two-step residual-based approach. Specifically, we use the residuals obtained from Regression Eq. 2, denoted as $\hat{\varepsilon}_{it}$, as the dependent variable in a second-stage regression:

$$\hat{\varepsilon}_{it} = a + \gamma CC_{it} + u_{it} \tag{3}$$

In this framework, the first-stage regression controls for the influence of macroeconomic and financial variables on sovereign bond yield spreads. The resulting residuals represent the component of the spread that cannot be explained by macro-financial factors. Regressing these residuals on climate-related variables (CC_{it}), our objective is to isolate and identify any independent effect that may influence sovereign bond yield spreads.

The results show that the variables contribute to the model specification, as the optimal lambda corresponded to a solution where the coefficients were not reduced to zero. This suggests that each variable contains relevant information to explain spread determinants in our sample.

According to the Modified Wald test for group wise heteroskedasticity and the Wooldridge test for autocorrelation in panel data, for Model Eq. 2, we find evidence of heteroskedasticity (p-value< 0.001) and autocorrelation of first order (p-value< 0.001). Moreover, in order to assess the CD issue, according to Pesaran (2021) and Menegaki (2018), we perform the Pesaran CD test, due to small $N = 19$ and $T = 29$ of dataset. We find a strong evidence of CD across the countries composing the dataset (p-value< 0.001). For these reasons, we perform the econometric analysis using Driscoll-Kraay estimator, according to Hoechle (2007): in this way, since the residuals are already corrected for heteroskedasticity, autocorrelation, and cross-sectional dependence, the second-stage estimates (Model Eq. 3) are robust to common statistical concerns in panel data settings. We estimate the fixed effect (FE) model following the results of the Hausman test, which rejects the null hypothesis of non-systematic differences in coefficients between FE and RE (random effects) estimator.

In Model Eq. 3, we include the climate variables one at a time to examine their individual effects on the residuals, which capture the component of the spread not explained by macro-financial factors. This approach is motivated by the high correlation among some of the climate variables, which could otherwise distort the estimation results if included simultaneously.

Based on theoretical considerations in Section 3, we expect E, REN, READ, and possibly ENTR to have a negative impact on the spread, as they reflect greater environmental awareness, renewable energy adoption, and green innovation, which may reduce perceived sovereign risk. Conversely, we anticipate that CO_2 emissions, GHG per capita, VULN, and E3CI may have a positive effect, as they are indicative of higher exposure or vulnerability to climate-related risks. However, we acknowledge uncertainty regarding some variables. For example, the impact of ENTR may not be strictly negative, depending on how markets interpret innovation efforts. To this extent, the effect of the REN variable may also be ambiguous, as the expansion of renewable energy can initially entail substantial investment and transition costs that may temporarily increase fiscal pressures and perceived sovereign risk, before yielding longer-term benefits. This ambiguity is further reinforced by the substantial heterogeneity across countries in our sample, where the level of renewable penetration, the timing of adoption and the fiscal capacity to support the transition differ markedly between regions. Similarly, for TAX, higher fiscal revenues could signal either improved fiscal capacity to service debt, thus reducing spreads, or a potential drag on growth, which might increase them. In the same manner, GPB (general government primary balance) may have a positive or negative effect depending on how deficits or surpluses are perceived, particularly in relation to the allocation of public spending. The expected signs of the coefficients are summarized in Table 4.

Table 4 Expected coefficient signs

X	Expected sign	CC	Expected sign
$gGDP_{it}$	−	E_{it}	−
$DEBT_{it}$	+	$CO2_{it}$	+
INF_{it}	−	$GHGpc_{it}$	+
GPB_{it}	+/−	$ENTR_{it}$	+/−
TB_{it}	−	REN_{it}	+/−
TAX_{it}	+/−	$READ_{it}$	−
POL_{it}	−	$VULN_{it}$	+
		$E3CI_{it}$	+

Note: The table shows the expected coefficient signs for macro–financial and climate-related variables. For the definition of the variables, see Table 1

Table 5 Results of dynamic panel regression Model Eq.2

VARIABLES	$SPREAD_{it}$
$SPREAD_{it-1}$	0.3383***
	(0.115)
$DEBT_{it}$	0.0141
	(0.009)
$gGDP_{it}$	-0.1647**
	(0.064)
$INFL_{it}$	0.0186
	(0.069)
GPB_{it}	0.0667**
	(0.027)
TB_{it}	-0.0017
	(0.005)
TAX_{it}	0.0220
	(0.069)
POL_{it}	-1.8146
	(1.101)
Observations	368
Number of groups	19
R_w^2	0.538
TD (p-value)	0.000
Standard errors in parentheses	
*** p<0.01, ** p<0.05, * p<0.10	

Note: The table shows the results of Model Eq. 2. The lagged dependent variable is included to account for persistence over time. Driscoll–Kraay standard errors correct for heteroskedasticity, cross-sectional correlation, and serial correlation. The statistic TD reports the p-value of the joint significance test of time fixed effects

6 Results

In this section, we present the results of the models described in Section 5. In addition, we conduct several robustness checks to validate our findings.

6.1 Baseline results: Dynamic model specifications

Table 5 shows the results of Model Eq. 2. The autoregressive parameter of $SPREAD_{it-1}$ is positive and statistically significant, confirming the degree of persistence of sovereign risk premiums and highlighting the importance of controlling for stationarity in spread dynamics. As expected, the estimated value of the autoregressive parameter is not excessively high (0.3383), indicating that the series are not excessively persistent.

Turning to the contemporaneous determinants, the results broadly align with theoretical priors and previous empirical evidence. GDP growth (gGDP) enters with a negative and significant sign, suggesting that stronger economic performance mitigates vulnerability to default and reduces risk premia. The government primary balance as share of GDP (GPB) exerts a positive effect on spreads, indicating that larger deficits (or weaker primary balances) are associated with higher market risk assessments. In contrast, government debt as share of GDP, inflation, trade balance as share of GDP, the tax-to-GDP ratio and the political stability index do not exhibit significant effects in the dynamic specification. This is consistent with the view that these variables either adjust slowly over time or exert an indirect influence that becomes absorbed by the lagged dependent variable and the time fixed effects. The model fits the data well, explaining more than half of the within-country variation in sovereign spreads ($R_w^2 = 0.538$). Finally, the joint significance test of the time dummies (TD p-value = 0.000) confirms that common shocks, such as the global financial crisis, the euro area sovereign debt crisis and the COVID-19 pandemic, represent key drivers of sovereign risk across the euro area. Their strong significance highlights the importance of controlling for shared temporal factors when analyzing the determinants of sovereign spreads.

We use the residuals from Model Eq. 2, that represent the component of the 10-year bond yield spread against the German benchmark that is not explained by macro-financial variables, to assess whether climate-related factors help to account for this unexplained variation. Table 6 shows the estimates obtained by regressing the residual component of sovereign spreads on each climate-related indicator. This approach isolates the contribution of climate variables from traditional determinants of sovereign risk and enables us to assess whether climate risks or climate performance exert an additional effect on the evolution of sovereign bond spreads. Overall, the results show that several climate dimensions are priced by sovereign bond markets even after controlling for macroeconomic fundamentals, fiscal conditions, and common shocks.

First, the Environmental score (E) exerts a strong and statistically significant negative effect on the unexplained component of spreads. The coefficient (-0.0343) implies that countries with higher environmental performance tend to exhibit lower sovereign risk once traditional determinants are accounted for. Specifically, a one-unit increase in the Environmental Score reduces the unexplained component of sovereign spreads by 0.0343 percentage points. This finding supports the idea that financial markets reward stronger environmental governance, or interpret better environmental performance as a signal of long-term resilience and policy credibility.

Second, the renewable energy share (REN) displays a positive and weakly significant coefficient (0.0172). This result is consistent with the ex-ante discussion on transition costs reported in Section 4 and driven by countries in earlier stages of renewable deployment that may face substantial short-term fiscal or structural adjustments that increase sovereign risk. The positive sign therefore reflects the transitional nature of the energy shift, especially in countries far from their long-term renewable targets, and aligns with the pronounced heterogeneity documented in the dataset.

Table 6 Results of Model Eq. 3 with contemporaneous climate variables

CC_{it}	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$
E_{it}	-0.0343***							
	(0.013)							
$ENTR_{it}$		-0.1111						
		(0.137)						
REN_{it}			0.0172*					
			(0.009)					
$READ_{it}$				-0.0195**				
				(0.010)				
$CO2_{it}$					0.0361***			
					(0.010)			
$GHGpc_{it}$						0.0369*		
						(0.020)		
$E3CI_{it}$							0.1892*	
							(0.114)	
$VULN_{it}$								0.1110***
								(0.036)
Constant	2.7517***	0.2964	-0.2672	1.0849*	-0.9329***	-0.3805*	-0.0283	-3.7077***
	(1.033)	(0.378)	(0.192)	(0.556)	(0.267)	(0.230)	(0.096)	(1.192)
Observations	357	368	321	368	361	368	368	368
R^2	0.0195	0.0018	0.0102	0.0106	0.0375	0.0089	0.0075	0.0259
R^2_a	0.0167	-0.0009	0.0071	0.0079	0.0348	0.0062	0.0048	0.0232

Standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Note: The table shows the results of Model Eq. 3. The dependent variable is the residual $\hat{\varepsilon}_{it}$ from Model Eq. 2

Third, the Readiness Index of ND-GAIN (READ) is negative and statistically significant (-0.0195), suggesting that countries with higher adaptive capacity and better preparedness for climate change tend to have lower unexplained spreads. This finding reinforces the role of structural resilience and institutional preparedness in mitigating long-term climate vulnerabilities perceived by investors. Moreover, the Vulnerability Index of ND-GAIN (VULN) exhibits a positive and significant effect (0.1110). In particular, a one-unit increase in the ND-GAIN Readiness Index reduces the unexplained component of sovereign spreads by 0.0195 percentage points. By contrast, a one-unit increase in the ND-GAIN Vulnerability Index increases the unexplained component of sovereign spreads by 0.1110 percentage points. These results confirm that climate-related vulnerabilities and exposure to climate shocks remain important predictors of sovereign risk, even after controlling for macroeconomic fundamentals. Countries structurally more exposed to climate hazards face higher perceived risk, according to the literature on climate vulnerability and sovereign spreads.

Fourth, the emissions-based indicators (CO2 and GHGpc) show positive and significant coefficients (0.0361 and 0.0369, respectively), indicating that higher emissions are associated with higher sovereign risk. While both indicators matter, GHGpc tends to be less significant than CO2, suggesting that markets may react more strongly to the overall carbon intensity of the economy rather than to per-capita emissions alone. The significance of these variables may reflect the perception of investors that high-emission countries show a lower propensity to transition, signaling weaker investment in green technologies, greater exposure to future mitigation costs, or more limited progress in decarbonization. In addition, the stronger effect of CO2 emissions might also capture broader environmental conditions, such as pollution levels and related implications for economic productivity and quality of life, which can be priced into sovereign risk assessments. In economic terms, a 0.1 increase in CO_2 emissions as a share of GDP is associated with an increase of about 0.361 percentage points in the unexplained component of sovereign spreads. Similarly, a one-unit increase in per-capita greenhouse gas emissions is associated with an increase of about 0.0369 percentage points in the unexplained component of sovereign spreads, corresponding to about 3.7 basis points.

Finally, the E3CI indicator, used as a proxy for the exposure of countries to physical climate risks, shows a positive but weakly significant coefficient (0.1892). This suggests that markets may recognize the relevance of physical vulnerability, although its pricing appears limited compared to other climate-related dimensions. The estimated coefficient implies that a one-unit increase in the E3CI is associated with an increase of about 0.189 percentage points in the unexplained component of sovereign spreads, corresponding to roughly 19 basis points. However, given the weak statistical significance of this result, its economic interpretation should be treated with caution.

In contrast, the ENTR variable (Environmentally Related Tax Revenue as a share of GDP) is not significant, indicating that the current level of environmentally related taxation does not appear to influence the unexplained component of sovereign spreads.

Taken together, these findings reveal that climate factors contribute meaningfully to the unexplained variation in sovereign spreads and that their effects differ across dimensions. Although strong environmental performance and climate readiness reduce sovereign risk, high emissions, elevated climate vulnerability, and transitional pressures associated with renewable deployment increase perceived sovereign risk. The generally low R^2 values are consistent with a residual-based specification and indicate that each climate variable captures a specific, but non-negligible, component of sovereign risk beyond traditional fundamentals.

In summary, our results show that climate-related variables help explaining the unexpected component of 10-year sovereign bond spreads, indicating that climate risk is indeed priced by financial markets beyond standard macroeconomic and fiscal fundamentals. Surprisingly, physical climate risk, proxied by the E3CI indicator, displays a positive and (albeit weakly) significant coefficient, suggesting that higher exposure to climate-related hazards is associated with higher sovereign risk, even after controlling for macroeconomic fundamentals. Other climate variables behave in line with existing literature, with better environmental performance and greater climate readiness associated with lower spreads, and higher emissions and structural vulnerability associated with higher perceived sovereign risk.

6.2 Robustness

We implement several robustness tests for the two previous models. In particular, we investigate the possibility of delayed effects of climate variables in Subsection 6.2.1; the effect of extreme physical risks in Subsection 6.2.2; the effect of renewable energy as share of GDP by terciles in Subsection 6.2.3 and the effect of Environmentally Related Tax Revenue as share of GDP by terciles in Subsection 6.2.4.

6.2.1 Lagged climate variables

In order to take into account the possibility that the effects of climate variables may be delayed, we regress the residuals obtained from Regression Eq. 2, the component of the spread that cannot be explained by macro-financial factors, on one-period lagged climate risk variables:

$$\hat{\varepsilon}_{it} = a + \gamma CC_{it-1} + u_{it} \quad (4)$$

This robustness check is important for several reasons. On the one hand, a key limitation of annual climate indicators is the loss of contemporaneity relative to macro-financial variables, which evolve at much higher frequencies. Climate performance, emissions, vulnerability, and environmental policies adjust slowly over time, and annual data may therefore mask short-term dynamics or generate temporal misalignment between climate conditions and sovereign risk. On the other hand, the effects of climate-related characteristics on financial markets are likely to be delayed, either because investors incorporate climate information gradually or because climate indicators themselves reflect underlying structural processes that unfold over longer horizons. The results are shown in Table 7 and are very similar to the results reported in Table 6 for the baseline model. Overall, the climate dimensions that were significant in the contemporaneous regressions remain significant once lagged, supporting the robustness of the climate–sovereign spread relationship. First, the lagged Environmental Score (E_{it-1}) continues to have a negative and highly significant effect on the residual component of sovereign spreads, with a magnitude very similar to the contemporaneous specification: a one-unit increase in the Environmental Score implies a reduction of roughly 0.037 in the unexplained component of sovereign spreads, indicating that stronger environmental performance continues to be associated with lower sovereign risk even when considering delayed effects. This reinforces the interpretation that better environmental performance reduces sovereign risk and suggests that markets internalize this information with some persistence.

Second, the renewable energy share (REN_{it-1}) remains positive and marginally significant, as in the baseline model. The stability of this coefficient across specifications indicates that the relationship between renewable deployment and sovereign risk, potentially reflecting transitional costs or structural adjustment frictions, persists even when accounting for delayed effects.

Third, the ND-GAIN Readiness Index (READ_{it-1}) retains its negative and statistically significant coefficient (-0.0199), again aligning with the contemporaneous results. In economic terms, a one-unit increase in the lagged Readiness Index reduces

Table 7 Results of Model Eq.4 with lagged climate variables

CC_{it-1}	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$
E_{it-1}	-0.0367***							
	(0.013)							
ENTR_{it-1}		-0.1363						
		(0.140)						
REN_{it-1}			0.0166*					
			(0.010)					
READ_{it-1}				-0.0199**				
				(0.010)				
$\mathrm{CO2}_{it-1}$					0.0347***			
					(0.009)			
GHGpc_{it-1}						0.0369*		
						(0.020)		
$\mathrm{E3CI}_{it-1}$							0.0930	
							(0.115)	
VULN_{it-1}								0.1158***
								(0.035)
Constant	2.9415***	0.3649	-0.2462	1.0997**	-0.9161***	-0.3518	-0.0117	-3.8765***
	(1.039)	(0.387)	(0.199)	(0.549)	(0.265)	(0.231)	(0.096)	(1.187)
Observations	348	368	306	368	368	368	368	368
R^2	0.0225	0.0026	0.0089	0.0112	0.0360	0.0076	0.0018	0.0285
R_a^2	0.0196	-0.0002	0.0056	0.0085	0.0334	0.0048	-0.0010	0.0258

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.10

Note: The table shows the estimates of Model Eq.4. The dependent variable is the residual $\hat{\varepsilon}_{it}$ from Model Eq.2.

the unexplained component of sovereign spreads by about 0.0199 percentage points, corresponding to roughly 2 basis points. Coherently, the ND-GAIN Vulnerability Index (VULN_{it-1}) remains positive and highly significant (0.1158), mirroring the contemporaneous specification. Economically, a one-unit increase in the lagged Vulnerability Index increases the unexplained component of sovereign spreads by about 0.1158 percentage points, corresponding to roughly 11.6 basis points. These results suggest that the two indicators capture particularly well the combined effects of institutional preparedness and structural exposure to climate risks on sovereign risk (e.g., Kling et al., 2025; Cevik and Jalles, 2022; Beirne et al., 2021; Naifar, 2023). In other words, countries that are better equipped to adapt to climate change tend to face lower spreads, whereas structurally vulnerable countries are consistently penalized by financial markets. Fourth, the emissions-based indicators continue to show strong effects: $\mathrm{CO2}_{it-1}$ remains positive and highly significant (0.0347), while GHGpc_{it-1} maintains a positive and marginally significant coefficient (0.0369). These results are consistent with the earlier evidence and indicate that high-emission profiles, whether measured in aggregate or per capita, are robust predictors of higher sovereign risk, with effects that persist across time. Economically, a 0.1 increase in CO_2 emissions as a share of GDP is associated with an increase of about 0.35 percentage points in the unexplained component of sovereign spreads, corresponding to roughly 35 basis points. Likewise, a one-unit increase in per-capita greenhouse gas emissions is associated with an increase of about 0.037 percentage points in sovereign spreads, corresponding to approximately 3.7 basis points. Regarding physical climate risk, the lagged $\mathrm{E3CI}_{it-1}$ variable becomes statistically insignificant, while it was weakly significant in the contemporaneous model. This attenuation suggests that physical risks might be priced more contemporaneously, possibly because extreme events or environmental shocks have immediate visibility, while their lagged effects are less clearly internalized by markets when only annual data are available. Finally, the ENTR variable continues to be not statistically significant, suggesting that environmentally related taxation does not appear to influence sovereign spreads in either specification. Taken together, these findings indicate that the main climate determinants of sovereign spreads are robust to temporal shifts, although the significance of physical risk weakens when lagged. This supports the idea that transition-related and governance-based dimensions have more persistent effects on sovereign risk, whereas physical risk may influence financial markets in a more immediate, event-driven manner.

6.2.2 Extreme physical risk

In order to analyze the effect of extreme physical risk and given that values of E3CI greater than 1 indicate anomalies that exceed inter annual values, we create a dummy variable, $\mathrm{E3CIdummy}_{it}$, which equals 1 if E3CI is greater than or equal to 1, and 0 otherwise. This approach allows us to examine the effect of E3CI even when its value indicates a critical level of exposure to physical climate risk. Therefore, we estimate both a contemporaneous and a lagged regression models, as follows:

$$\hat{\varepsilon}_{it} = a + \gamma \mathrm{E3CI}_{it} + \delta \mathrm{E3CIdummy}_{it} + u_{it} \tag{5}$$

$$\hat{\varepsilon}_{it} = a + \gamma \mathrm{E3CI}_{it-1} + \delta \mathrm{E3CIdummy}_{it-1} + u_{it} \tag{6}$$

The results of Models Eqs. 5 and 6, shown in Table 8, indicate that the introduction of a threshold dummy for physical climate risk does not improve the explanatory power of E3CI. In the contemporaneous specification, the contemporaneous E3CI indicator is weakly significant and positive, confirming the baseline evidence that higher exposure to physical climate hazards is associated with higher sovereign spreads. When the analysis is repeated using lagged values, both the contemporaneous E3CI indicator ($\mathrm{E3CI}_{it-1}$) and its threshold counterpart ($\mathrm{E3CIdummy}_{it-1}$) are not significant. Therefore, the results highlight that extreme physical risk, even when considered in lagged terms, does not explain the unexplained component of the spread.

6.2.3 A focus on cross-country diverges in renewable energy share and environmentally related tax revenue as share of GDP

In this section, we investigate the role of Renewable Energy Share (REN) and Environmentally Related Tax Revenue as share of GDP (ENTR). REN and ENTR are the variables most directly linked to climate policy and, to some extent, to transition risk.

Table 8 Results of Models Eqs. 5 and 6 for Extreme physical risk

VARIABLES	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$
E3CI_{it}	0.2663*	
	(0.141)	
E3CIdummy_{it}	-0.7408	
	(0.807)	
E3CI_{it-1}		0.1158
		(0.152)
E3CIdummy_{it-1}		-0.2497
		(1.079)
Constant	-0.0237	-0.0112
	(0.096)	(0.096)
Observations	368	368
R^2	0.0098	0.0019
R_a^2	0.0044	-0.0036

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.10

Note: The table shows the results of Models Eqs.5 and 6. The dependent variable is the residual $\hat{\varepsilon}_{it}$ from Model Eq.2

As such, they are shaped by structural country-specific fundamentals, reflecting heterogeneous policy strategies, energy systems, and fiscal frameworks. In other words, these two indicators largely depend on the type of country considered. Consistently, as shown in Table 1, REN and ENTR exhibit high cross-country dispersion among the climate-related indicators, suggesting that their effect on sovereign spreads may differ substantially across countries. This heterogeneity is visually confirmed in Figs.

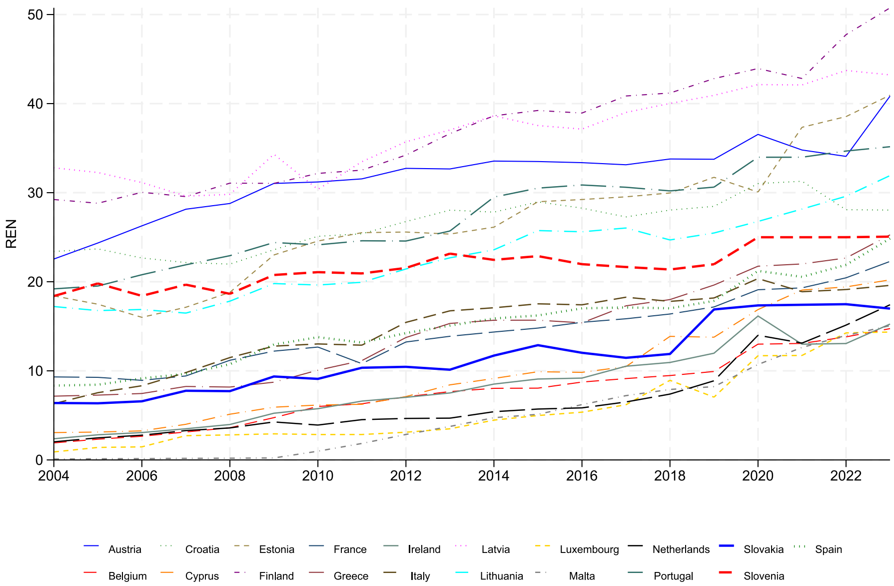


Fig. 4 Renewable Energy Share from 2004 to 2023. *Note:* The figure shows the Renewable Energy Share over the period 2004–2023

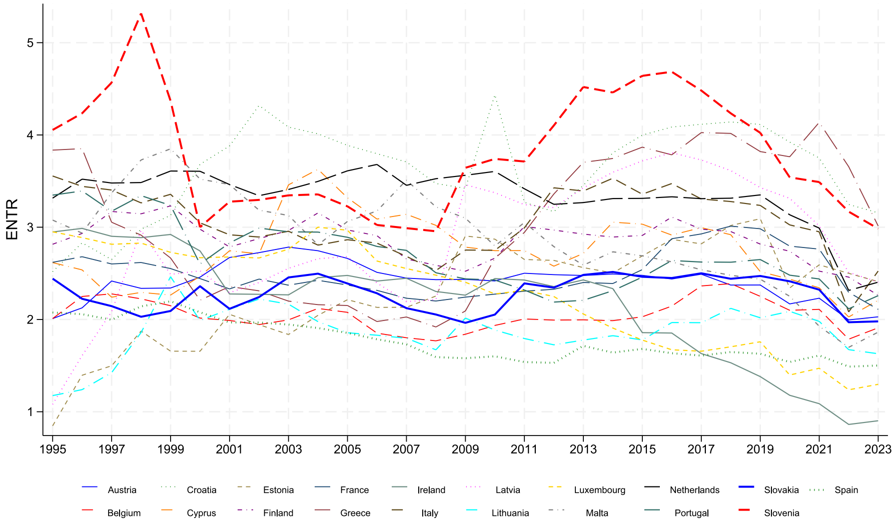


Fig. 5 Environmentally Related Tax Revenue as share of GDP from 1995 to 2023. *Note:* The figure shows the Environmentally Related Tax Revenue as share of GDP over the period 1995–2023

4 and 5, which plot the evolution over time of REN and ENTR, respectively for each countries. The yearly trajectories of the renewable energy share (Fig. 4) display marked differences across countries, with some exhibiting rapid increases over time and others showing much slower or more irregular dynamics. Such pronounced cross-country divergence indicates that the transition to renewable energy is far from being homogeneous within the sample. In particular, we observe countries starting from very low levels of renewable energy use (such as Luxembourg and Ireland), others with intermediate levels (such as Lithuania and Slovenia), and countries with consistently high values (such as Finland and Latvia). This divergence underscores the heterogeneity of the energy transition process across European countries. Overall, we observe an upward trend in renewable energy share across all countries, reflecting the broader European policy effort to accelerate the transition toward a greener and more sustainable economy. Considering the evolution of the environmentally related tax revenue as share of GDP, the cross-country patterns appear markedly heterogeneous and less systematic than those observed for REN. As shown in Fig. 5, environmental tax revenues as share of GDP fluctuate considerably over time, with some countries presenting relatively stable and persistently low levels (e.g., Luxembourg, Spain, Belgium), whereas others exhibit pronounced volatility or episodic spikes (notably Estonia and Croatia). Unlike the clear upward trend observed for renewable energy, ENTR does not display a common directional pattern across the sample. For many countries, environmental taxation rises in the early 2000s, then stabilizes or even declines after 2010, suggesting that national fiscal structures and policy reforms play a central role in shaping the dynamics. The absence of a uniform trajectory across Europe highlights the strong dependence of ENTR on country-specific tax frameworks, policy priorities, and institutional settings, rather than on a shared, EU-wide transition path. In order to investigate the cross-country differences, we split

countries into three groups (terciles) based on the amount of their REN (ENTR): a low-REN (low-ENTR) group, a medium-REN (medium-ENTR) group and a high-REN (high-ENTR) group. Then, we estimate Models Eqs. 3 and 4 for each group. We opt for terciles to ensure a sufficient number of observations within each group for a meaningful econometric analysis.

The results shown in Table 9 confirm a marked heterogeneity in the relationship between renewable energy and the unexplained component of sovereign spreads across the terciles. In the low-REN group (Belgium, Cyprus, Ireland, Luxembourg, Malta, Netherlands, Slovakia), the coefficients on REN are small and not statistically significant, suggesting that, for countries at an early stage of the energy transition, the renewable share does not yet convey a clear signal to investors about sovereign risk beyond macro-financial fundamentals. In the medium-REN group (France, Greece, Italy, Lithuania, Slovenia, Spain), both contemporaneous and lagged REN are positive and statistically significant (0.1133 and 0.1083, respectively). In particular, a one-unit increase in the share of renewable energy is associated with an increase of about 0.113 percentage points in the unexplained component of sovereign spreads, corresponding to roughly 11 basis points. A similar effect emerges for the lagged variable, whose coefficient implies an increase of about 10.8 basis points. This indicates that, for intermediate levels of renewable energy source, increases in the renewable share are associated with higher spreads, consistent with the idea that transition and adjustment costs, such as investment needs, structural reforms, or short-run inefficiencies, may temporarily raise perceived sovereign risk. By contrast, in the high-REN group (Austria, Croatia, Estonia, Finland, Latvia, Portugal), the contemporaneous coefficient on REN is negative and significant (-0.0467), while the lagged effect is not significant. Economically, this implies that a one-unit increase in the renewable energy share reduces the unexplained component of sovereign spreads by approximately 0.047 percentage points, corresponding to about 4.7 basis points.

Table 9 Effect of Renewable Energy Share by terciles

VARIABLES	Low REN		Medium REN		High REN	
	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$
REN_{it}	0.0443		0.1133***		-0.0467**	
	(0.027)		(0.042)		(0.023)	
REN_{it-1}		0.0397		0.1083**		-0.0266
		(0.030)		(0.046)		(0.025)
Constant	-0.0934	-0.0366	-2.4421***	-2.2863***	1.8986***	1.2350
	(0.213)	(0.222)	(0.750)	(0.802)	(0.718)	(0.774)
Observations	118	112	111	106	92	88
R^2	0.0227	0.0157	0.0621	0.0499	0.0440	0.0127
R^2_a	0.0143	0.0068	0.0535	0.0408	0.0333	0.0012

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.10

Note: The table shows the results of Models Eqs.3 and 4, using the REN variable as regressor, obtained after grouping countries into three terciles based on their average renewable energy share. The resulting groups are: low-REN (Belgium, Cyprus, Ireland, Luxembourg, Malta, Netherlands, Slovakia), medium-REN (France, Greece, Italy, Lithuania, Slovenia, Spain), and high-REN (Austria, Croatia, Estonia, Finland, Latvia, Portugal). The dependent variable is the residual $\hat{\varepsilon}_{it}$ from Model Eq.2

These findings are economically meaningful and provide important insights into the transition process. In fact, they suggest that for countries that are already more advanced in the renewable transition, higher renewable energy share is associated with lower sovereign risk. This supports the idea that once a country surpasses a critical threshold of the transition, the benefits, such as greater energy resilience, reduced dependence on fossil fuels, and enhanced long-term sustainability, begin to dominate, ultimately lowering the risk perceived by financial markets. By contrast, countries that are still at an intermediate stage of renewable adoption appear to face higher borrowing costs. This pattern is consistent with the presence of significant upfront transition costs, such as infrastructure investment, technological upgrading, and regulatory adjustments, which may temporarily increase fiscal pressure and translate into higher sovereign risk premia.

Regarding environmentally related tax revenue as share of GDP, Table 10 reveals a substantially weak relationship between ENTR and the unexplained component of sovereign spreads. Across all terciles, contemporaneous ENTR is not statistically significant, indicating that variations in environmentally related tax revenues as a share of GDP do not systematically translate into changes in sovereign risk once macro–financial fundamentals are accounted for. In the low-ENTR group (Belgium, Estonia, Ireland, Lithuania, Luxembourg, Slovakia, Spain) and in the high-ENTR group (Croatia, Greece, Italy, Malta, Netherlands, Slovenia), both contemporaneous and lagged ENTR coefficients are not significant, suggesting that environmental taxation is not relevant for sovereign risk. Instead, in the medium-ENTR group (Austria, Cyprus, Finland, France, Latvia, Portugal), the lagged ENTR is positive and statistically significant (0.7333): a one-unit increase in environmentally related tax revenues as a share of GDP is associated with an increase of about 0.733 percentage points in the unexplained component of sovereign spreads, corresponding to roughly 73 basis

Table 10 Effect of Environmentally Related Tax Revenue as Share of GDP by terciles

VARIABLES	Low REN		Medium REN		High REN	
	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$	$\hat{\varepsilon}_{it}$
ENTR_{it}	0.3918		0.4768		0.3699	
	(0.345)		(0.320)		(0.374)	
ENTR_{it-1}		0.4501		0.7333**		0.1606
		(0.366)		(0.326)		(0.383)
Constant	-0.4009	-0.5303	-1.5024*	-2.2038**	-1.4595	-0.7692
	(0.718)	(0.768)	(0.882)	(0.898)	(1.255)	(1.286)
Observations	130	130	123	123	115	115
R^2	0.0100	0.0117	0.0180	0.0402	0.0086	0.0016
R^2_a	0.0022	0.0040	0.0099	0.0323	-0.0002	-0.0073

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.10

Note: The table shows the results of Models Eqs.3 and 4, using ENTR as regressor, obtained after grouping countries into three terciles based on their average environmentally related tax revenue as share of GDP. The resulting groups are: low-ENTR (Belgium, Estonia, Ireland, Lithuania, Luxembourg, Slovakia, Spain), medium-ENTR (Austria, Cyprus, Finland, France, Latvia, Portugal), and high-ENTR (Croatia, Greece, Italy, Malta, Netherlands, Slovenia). The dependent variable is the residual $\hat{\varepsilon}_{it}$ from Model Eq.2

points, potentially reflecting short-run fiscal pressures or policy adjustments associated with environmental tax reforms.

Overall, these results suggest that environmentally related tax revenue as share of GDP is not perceived by markets as a direct driver of the energy transition. If at all, increases in ENTR, particularly in the medium-ENTR group, where the lagged coefficient becomes significant, appear to be interpreted more as an intensification of the overall tax burden rather than as a policy supporting climate mitigation. It is also noteworthy that the country grouping based on ENTR differs substantially from the terciles obtained using renewable energy shares. For instance, Italy, Slovenia and Greece belong to the highest ENTR tercile but fall into the medium tercile for renewable energy, illustrating that environmental tax revenues reflect fiscal structures and policy choices rather than the actual progress of the energy transition. This further supports the view that ENTR captures country-specific fiscal architectures rather than transition dynamics, thereby limiting its relevance for sovereign risk pricing.

7 Discussion and conclusions

In this study, we provide evidence that the 10-year sovereign bond yield spread against the German benchmark is influenced by climate related variables. The main contribution of this work lies in the inclusion of a broader and more diverse set of climate-related variables than those typically used in previous empirical studies. Drawing on both public and private data sources, we incorporate eight climate variables in our analysis, five of which have not been used in earlier research: as a proxy of transition risk, we use the LSEG Refinitiv Environmental Score, the greenhouse gas (GHG) emissions per capita, the renewable energy share and environmentally related tax revenue as a share of GDP; as a proxy of physical risk, the E3CI index as a proxy for physical risk. This expanded framework allows for a more comprehensive assessment of the channels through which climate factors can affect sovereign bond spreads. Moreover, our analysis is focused exclusively on Euro Area countries. All of them operate within a shared policy framework and are part of the European Union, which has implemented the most ambitious and coordinated green transition agenda worldwide.

Unlike previous studies, we employ a two-step approach. First, we use a dynamic linear regression model to epurate the spread from macro-financial variables. This allows us to isolate the unexplained component of the spread. Second, we use the residuals in a subsequent regression analysis (residual-based approach) against climate variables to assess whether the climate variables are related to the unexplained component of the spread.

We find several key results that shed light on the relationship between climate-related variables and sovereign bond spreads. First, the Environmental Score has a negative association with the unexplained component of spread: countries with higher scores, indicating stronger environmental performance, tend to experience lower spreads. This supports the idea that environmental quality is perceived as a factor of financial stability. Economically, a strong environmental profile may signal lower long-term transition costs and reduced exposure to environmental liabilities that investors interpret as improving a country's fiscal outlook and reducing default risk. In this sense, environmental performance acts as a forward-looking indicator of macro-financial resilience, which markets reward through lower risk premia.

In contrast, CO_2 emissions as a percentage of GDP and GHG emissions per capita have a positive association with the unexplained component of spread. This result is highly policy-relevant: it might suggest that financial markets penalize countries that delay decarbonization or remain structurally dependent on fossil-fuel–intensive production. In this sense, emissions serve not only as environmental indicators but also as forward-looking fiscal and macro-financial signals, reflecting concerns about future mitigation costs, exposure to transition policies, and potential losses in competitiveness. These findings reinforce the idea that accelerating emissions reduction is not merely an environmental imperative but a condition increasingly tied to a country's sovereign financing conditions.

Our findings also confirm the importance of institutional preparation. The ND-GAIN variables, measuring readiness (READ) and vulnerability (VULN), in line with the existing literature (Kling et al. 2025; Cevik and Jalles 2022), are both statistically significant with readiness showing a negative coefficient and vulnerability a positive one. However, vulnerability displays stronger explanatory power than readiness, implying that a country's inability to cope with climate challenges plays a more decisive role than its level of resilience.

A key contribution of the paper concerns the role of renewable energy in shaping sovereign risk. While the baseline residual-based specification shows a positive and mildly significant association between the renewable energy share (REN) and the unexplained component of spreads, our deeper investigation reveals that this aggregate effect masks substantial cross-country heterogeneity. By splitting countries into terciles according to their average renewable energy share, we show that the relationship between REN and sovereign spreads is far from uniform across Euro Area countries. In countries at an early stage of the transition, increases in renewable deployment do not convey a clear signal to investors, while in intermediate REN countries the transition appears to generate short-term adjustment frictions that are priced as higher sovereign risk. Conversely, in the group of countries most advanced in the energy transition, renewable expansion is instead associated with lower spreads, consistent with the notion that once a critical threshold is reached, the macro-financial benefits of renewable deployment (including greater energy resilience, reduced exposure to fossil-fuel shocks and improved long-term sustainability) dominate transitional costs. Taken together, these results suggest that financial markets price the renewable transition in a non-linear and state-dependent way: the impact of renewable energy on sovereign risk depends critically on each country's structural position along the transition path.

Moreover, we investigate the effect of Environmentally Related Tax Revenue as a share of GDP (ENTR) on the unexplained component of the spread. In the baseline specification, ENTR is not statistically significant, indicating that environmental taxation does not exert a systematic influence on sovereign risk once macro–financial fundamentals are accounted for. A more detailed analysis based on country terciles confirms this finding. Across most groups, both contemporaneous and lagged ENTR coefficients remain not significant. Only in the medium-ENTR group the lagged

Table 11 Standardized beta coefficients

Variable	Model Eq. 3	Model Eq.4
Panel A. Baseline climate indicators		
E	-0.1395***	-0.1498***
ENTR	-0.0423	-0.0507
REN	0.1009*	0.0943*
READ	-0.1029**	-0.1057**
CO_2	0.1936***	0.1899***
GHGpc	0.0944*	0.0869*
E3CI	0.0866*	0.0421
VULN	0.1610***	0.1688***
Panel B. Renewable energy share by tercile		
Low REN	0.1508	0.1254
Medium REN	0.2493***	0.2234**
High REN	-0.2097**	-0.1127
Panel C. Environmentally related tax revenue by tercile		
Low ENTR	0.0999	0.1082
Medium ENTR	0.1343	0.2006**
High ENTR	0.0926	0.0394

*** p<0.01, ** p<0.05, * p<0.10

Note: The table shows standardized beta coefficients for Models Eqs.3 and 4. The coefficients are derived from the regressions reported in Tables 6, 7, 9, and 10

ENTR coefficient is positive and significant, suggesting an increase in the unexplained component of the spread, but the absence of a contemporaneous effect and the lack of robustness across terciles suggest that this pattern may reflect temporary fiscal pressures or isolated policy adjustments rather than a structural relationship. Taken together, these results indicate that environmental taxation is not perceived by financial markets as a direct driver of the energy transition: higher ENTR levels may be interpreted more as an increase in the general tax burden than as a climate policy instrument with implications for sovereign risk.

Finally, concerning the E3CI index, used as a proxy of physical risk exposure, we find that a country with higher physical risk tends to experience higher spread, suggesting that physical risk might still be partially priced by sovereign bond markets. The weak significance in the baseline specification vanishes once the lagged E3CI is considered. Accounting for extreme physical risk through threshold models has no explanatory power, suggesting that annual indicators of physical exposure may not fully capture the financial relevance of climate-related natural hazards.

In order to compare the economic relevance of the climate indicators on a common scale, we report in Table 11 the standardized beta coefficients of Models Eqs. 3 and 4. This transformation allows a direct comparison of the relative importance of variables measured on different scales[8]. The results show that CO_2 intensity is the most

[8] We complement the basis-point interpretation in Tables 6-10 with standardized beta coefficients, obtained by standardizing both the dependent variable and each climate indicator to have zero mean and unit standard deviation. As discussed by Liu and Winegar (2025), conventional economic magnitude obtained by multiplying the non-standardized beta coefficient by the sample standard deviation may be problematic in panel regressions with fixed effects, since the overall standard deviation can exceed the within-group

economically relevant positive driver of sovereign spreads in both specifications, with standardized beta coefficients of 0.1936 in Model Eq. 3 and 0.1899 in Model Eq. 4. Higher carbon intensity can be interpreted as a proxy for greater exposure to transition risk, since more carbon-intensive economies are likely to face higher adjustment costs, stronger regulatory pressure, and potentially larger fiscal burdens in the transition toward a low-carbon economy.

On the mitigating side, the Environmental Score emerges as the strongest factor associated with lower sovereign spreads, with standardized coefficients ranging from -0.1395 to -0.1498, while the Readiness Index exerts a meaningful negative effect, although smaller in absolute value, with coefficients between -0.1029 and -0.1057. By contrast, the Vulnerability Index displays a sizeable positive association, with standardized betas between 0.1610 and 0.1688, confirming that climate-exposed countries are strongly penalized by financial markets. The fact that vulnerability exerts a stronger positive effect on sovereign spreads than readiness indicates that markets appear to penalize structural climate fragility more than they reward adaptive capacity. In other words, investors may perceive exposure to climate-related damages as a more immediate and salient source of sovereign risk than the mitigating role played by preparedness and institutional resilience. On the other hand, the Environmental Score appears to capture a broader signal of environmental quality and policy credibility, thereby acting as the main mitigating factor. Greenhouse gas emissions per capita and the E3CI index display comparatively smaller and less robust effects: both are only weakly significant in the contemporaneous specification, while the E3CI index loses significance in the lagged model.

The tercile analysis further reveals substantial heterogeneity in the effects of renewable energy and environmentally related tax revenue across groups of countries. For renewable energy, standardized beta coefficients are positive in the middle tercile (0.2493 in the contemporaneous specification and 0.2234 in the lagged one) and are negative in the high-renewables tercile (-0.2097 in the contemporaneous model). By contrast, environmentally related tax revenue is not significant, with the only notable exception being the lagged specification for the middle tercile, where the standardized beta is equal to 0.2006. The heterogeneous tercile results for renewable energy suggest that policy-related indicators are not priced uniformly across countries, but depend on initial conditions and country-specific structural characteristics. Overall, the evidence points to a clear distinction between structural sources of climate risk, which are more strongly priced by sovereign markets, and broader environmental-policy indicators, whose effects appear to depend more strongly on country-specific economic fundamentals.

This study offers valuable information for European policymakers seeking to understand the financial risks posed by climate change, while also providing actionable guidance for the design of effective climate-financial strategies. First, we show that climate risk is priced within the Euro Area, a group of advanced economies

variation and thus overstate economic magnitudes. In our case, this concern is amplified by the use of a second-stage pooled regression of the residual component, which makes the choice between overall and within standard deviation less clear-cut. Therefore, we resort to standardized beta coefficients to compare the relative importance of variables measured on different scales without imposing an arbitrary scaling rule.

characterized by high institutional quality, fiscal stability, and a common monetary framework. Climate risk is not only a concern for emerging or structurally fragile countries, but it is internalized by financial markets also where institutional capacity is high and macroeconomic conditions are relatively stable. Second, our evidence indicates that accelerating the reduction of carbon emissions may contribute not only to achieving climate objectives but also to lowering sovereign financing costs. Financial markets appear to penalize countries characterized by persistently high-emission profiles, signaling concerns about delayed decarbonization, future mitigation costs and structural dependence on fossil-fuel-intensive production (see Collender et al., 2023). In this sense, emissions are interpreted as forward-looking indicators of technological progress and productive innovation, key drivers of long-term economic growth.

Third, the non-linear relationship between renewable energy share and sovereign spreads highlights the importance of sustained and credible transition pathways. Countries in the intermediate stage of the energy transition may temporarily face higher borrowing costs, reflecting the short-term fiscal and structural adjustments required to reshape their energy systems. However, our results suggest that these costs decline once a country reaches a sufficiently advanced stage of renewable penetration, at which point the macro-financial benefits of the transition (e.g., greater energy resilience, reduced exposure to fossil-fuel shocks, and improved long-run sustainability) begin to dominate. These dynamics underscore the need to combine renewable investment policies with coherent fiscal and budgetary strategies that can cushion the short-term costs of transition. Finally, the behavior of environmental taxation reveals that, in its current form, environmentally related tax revenue does not constitute a meaningful determinant of sovereign spreads. Where significant, its effect tends to operate through channels related to general fiscal pressure rather than through climate-policy credibility or transition dynamics. In other words, environmental taxation does not appear to be the most effective standalone instrument to signal green transition progress to financial markets, as also found in Dogan et al. (2023), which shows that environmental taxes negatively impact renewable energy deployment. Our research complements the existing literature on climate risk and sovereign spreads, reinforcing the idea that markets reward credible climate performance and penalize delayed transition efforts. From a policy perspective, our results suggest that accelerating decarbonization should improve fiscal sustainability by lowering sovereign financing costs; moreover, renewable-energy strategies should be conceived as multi-stage, long-horizon processes supported by stable fiscal frameworks, while environmental taxation should be integrated into broader climate and industrial strategies rather than used as an isolated policy tool.

Future research could further explore these dynamics by leveraging higher-frequency data and spillover-based approaches, in order to capture more precisely the timing and cross-country transmission of climate-related risks in sovereign bond markets.

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Data Availability Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

Code availability Code will be made available on request.

Competing interests The authors declare no competing interests.

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