



Research article

Green bonds and their effectiveness: Mitigating emissions and enhancing sovereign ESG scores

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Abstract: In this study, we empirically investigated the dual impact of green bond issuances on greenhouse gas (GHG) emissions and sovereign Environmental, Social, and Governance (ESG) scores. Using a fixed-effects panel regression model for a global sample of countries from 2000 till 2022, we found that green bond issuance is correlated with a significant reduction in GHG emissions in the subsequent years. This negative effect is stronger in countries with higher levels of financial development. Furthermore, we documented a positive impact on sovereign ESG scores, though this effect is more pronounced in lower-income economies and diminishes with a country's development level. Heterogeneity analyses revealed that the credibility signal of external verification is context-dependent: Its value is greatest in markets where credibility is scarce, such as in lower-ESG or less financially developed countries. Our findings highlight that the efficacy of green bonds is not uniform but is critically shaped by a nation's economic structure, financial sophistication, and existing sustainability trajectory. These results offer nuanced policy implications for designing targeted green finance strategies to maximize their environmental and financial returns.

Key words: green bonds; greenhouse gas emissions; carbon emissions; sovereign ESG scores; effectiveness

JEL Codes: Q56, G23, O44

1. Introduction

The Paris Agreement establishes a global framework to curb emissions, striving for net-zero in the latter half of the century (UNFCCC, 2016). As of June 2024, 107 countries committed to achieving net-zero emissions, with many mid-century targets setting (Olhoff et al., 2024). The green bond (GB) market can accelerate this low-carbon transition (Banga, 2019).

Green bonds are bonds whose proceeds are committed to the financing of green projects (such as renewable energy, resource conservation, and the building of green facilities, among others). Therefore, beyond the mutual advantages for bond issuers and investors, GBs are expected to deliver environmental benefits as well. Therefore, they are key instruments for financing tremendous investments in climate finance (Tolliver et al., 2020; Rannou et al., 2021). According to the Climate Bond Initiative (CBI) report, the GB market reached a size of \$587.6 billion in 2023, doubling over the past five years (CBI, 2023¹).

Anticipating the environmental benefits of GBs, many countries view the GB market as a key policy tool for achieving carbon neutrality. Consequently, they are actively developing this market through legal frameworks and subsidies. This rapid development highlights the need to understand the effectiveness of GBs. For example, do GBs reduce greenhouse gas (GHG) emissions? Do GBs improve sovereign Environmental, Social and Governance (ESG) ratings in the following years?

Although the literature reports the negative relationship between GBs and carbon emissions on a firm level (Fatica & Panzica, 2021; Flammer, 2021) and state or country-level (Al Mamun et al., 2022; Alamgir & Cheng, 2023; Flammer, 2023; Ran & Zhang, 2023), they dominantly concentrate on carbon emissions. We use GHG and carbon dioxide (CO₂) with extensive data, including 173 countries for 22 years.

In addition, studies have shown that green bond issuance improves the ESG performance of issuing firms in subsequent years (Flammer, 2021; Yeow & Ng, 2021; Chen & Rahaman, 2022). However, to the best of our knowledge, no research has directly examined the relationship between green bond issuance and sovereign ESG scores. Understanding this link is essential, as it sheds light on the effectiveness of green bonds as an instrument of climate finance. We argue that green bond issuance can improve sovereign ESG scores through financial, governance, and signaling channels.

We find that GBs effectively reduce GHG and CO₂ emissions, with their impact on carbon reduction being nearly twice as strong as on overall GHG emissions. Moreover, GB issuances with a two- and three-year lag exhibit a similar effect, suggesting a long-term influence on carbon emissions. Additionally, (Flammer, 2023) the effectiveness of green bonds differs across countries and is closely linked to national income levels, primarily through the channel of financial development. In this context, the role of third-party verification is conditional on the degree of financial market development, with its advantages being most significant in highly developed economies.

Our findings reveal a positive and significant relationship between GB issuances and sovereign ESG scores, which persists even for issuances lagged by two years. Additionally, the positive effect of green bond issuance on sovereign ESG scores is not uniform across countries. The impact is weaker in high-income economies, where green bonds are expected, but stronger in countries with less developed financial markets, where issuance and verification send a more powerful signal of

¹ Climate Bonds Initiative (2024) Sustainable Debt Global State of the Market 2023, Climate Bonds Initiative. Available at: <https://www.climatebonds.net/files/documents/publications/Global-State-of-the-Market-Report-2023.pdf>.

sustainability commitment. Since higher ESG scores are associated with lower sovereign borrowing costs (Crifo et al., 2017), our results suggest that GB issuances may ultimately contribute to reducing a country's borrowing costs.

Our study makes three key contributions to the literature. First, unlike other researchers, we examine CO₂ and overall GHG emissions, recognizing that green bonds can mitigate not only carbon dioxide but a broader set of greenhouse gases. Second, we assess the role of country income levels and show that the effectiveness of green bonds is positively associated with the degree of financial development. Finally, we investigate the link between green bond issuance and sovereign ESG scores, addressing an important gap in the existing literature.

The remainder of the paper is organized as follows. In Section 2, we discuss a review of the prior literature most pertinent to our research questions. In Section 3, we present the data. In Section 4, we describe our empirical results. Finally, in Section 5, we provide concluding remarks.

2. Literature review

Literature on the relationship between GB issuance and decarbonization, while growing, presents a complex picture that varies significantly by the level of analysis—be it firm, sub-national, or country, and methodological approach.

At the micro and sub-national levels, Flammer (2023) found a significant 0.9–1.4% decrease in carbon emissions following issuance. This research highlights the role of third-party certification, finding certified GBs (certified by independent third parties) to be nearly twice as effective as their non-certified counterparts. This finding is corroborated in the Chinese context by Xu & Li (2023), whose 5-year analysis of city-level data revealed a significant negative impact on urban carbon emissions, particularly in economically developed cities. Similarly, Tang & Zhang (2020) found that GB-issuing firms in China experienced a significant improvement in their environmental performance compared to non-issuing peers.

Shifting to a macro, country-level perspective, research often employs panel regression models to uncover more heterogeneous effects that are contingent on national characteristics. Alamgir & Cheng (2023) demonstrated a consistent negative correlation between national GB issuance and carbon emissions, alongside a positive association with renewable energy production. The role of a country's developmental and institutional context is emphasized by Al Mamun et al. (2022), who estimated a more pronounced carbon reduction effect of GBs in developed and highly innovative markets. In addition, (Baştürk, 2024) also confirms the negative impact of GBs on carbon emissions by employing the system generalized method of moments (GMM).

Despite these valuable insights, the literature suffers from two major limitations. First, there is a geographic scarcity; most researchers focus on single countries (e.g., U.S., China) or groups of developed nations (OECD). Consequently, a comprehensive global analysis examining GB effectiveness across a full spectrum of economies, from high-income to developing nations, is notably absent.

Second, there is an emissions measurement gap. The overwhelming focus has been on CO₂ as the dependent variable. Little is known about the effectiveness of GBs in reducing overall GHG emissions, which include other potent pollutants like methane (CH₄). This is a critical omission, as research by Kwilinski et al. (2024) suggests that the green economy's market capitalization has its strongest impact on methane levels, indicating that the focus of green financing may affect different gases in different ways.

In the second part of our study, we examine the impact of GBs on sovereign ESG ratings. The positive relationship between issuing GBs and improvement in ESG ratings is studied on a firm-level (Flammer, 2021; Yeow & Ng, 2021; Chen & Rahaman, 2022). While there is no direct correlation between a country's GB issuances and its sovereign ESG score, a relationship can be expected through environmental and governance pillars of ESG scores.

A country's aggregate level of green bond issuance can positively influence its sovereign ESG score by signaling a whole-of-economy commitment to sustainability, which incentivizes and reflects broader policy shifts. While sovereign bonds directly signal government intent, corporate and financial green bonds demonstrate private sector mobilization, collectively creating a powerful narrative of national transition that ESG rating agencies incorporate into their assessments (OECD, 2020). This relationship is reinforced through several channels. Firstly, a thriving green bond market directly finances projects that improve national environmental performance (the "E" pillar), a key input for sovereign ESG scores (Kaminker, 2015). Secondly, the development of this market enhances the "G" pillar by fostering better climate-related financial governance, transparency, and regulatory frameworks as policymakers act to prevent greenwashing and attract capital (Gianfrate & Peri, 2019; Reboredo, 2018; Tolliver et al., 2019). Finally, a high volume of issuance signals to raters that the country has a mature sustainable finance ecosystem, which reduces transition risk and is viewed as a marker of economic resilience and forward-looking governance (Sartzetakis, 2021; Dill, 2023; Alvi et al., 2025). Therefore, we expect green finance activity provides a strong, measurable indicator of a nation's sustainability trajectory, thereby impacting its sovereign ESG rating.

It is important to empirically examine the impact of GBs on country ESG scores as it offers several insights about the benefits of GBs for a country except environmental benefits. For example, it is reported that ESG metrics are indirectly valuable for assessing a country's solvency (Semet et al., 2021) and can reduce borrowing costs (Crifo et al., 2017).

We aim to fill these gaps by conducting a truly global analysis encompassing 173 countries, 64 of which are GB issuers. Furthermore, we expand the dependent variable beyond CO₂ to include total GHG, providing a more holistic assessment of GB effectiveness in mitigating climate change. Finally, we explore the relationship between GB issuances and sovereign ESG scores.

3. Materials and empirical design

In this section, we present the data acquisition and cleaning procedures, followed by descriptive statistics. We also outline our empirical strategy to address the research questions.

3.1. Green bonds

GB issuance data are obtained from LSEG, formerly recognized as Refinitiv. We retrieve data from Refinitiv's Government & Corporate Bonds - Advanced Search app until 2021 by filtering the field "Green bond indicator" as "Yes".² The dataset includes all green-labeled corporate, non-U.S. municipal, and government bonds issued between 2000 and 2021, excluding supranational GB issuances. It covers 5,215 issuances in 75 unique countries, with the first recorded in 2008, except for

² LSEG identifies eligible green bonds whose use of proceeds are in line with the Paris Agreement and corresponding international guidelines by CBI and ICMA. See more: https://www.lseg.com/content/dam/ftse-russell/en_us/documents/ground-rules/ftse-emu-government-green-bond-select-index-ground-rules.pdf.

U.S. municipal bonds. However, we restrict our sample to 64 countries with positive green bond issuances and complete data on all control variables. There is an inherent difficulty in directly filtering green-labelled bonds for United States municipal bonds within LSEG, and hence, we use Statista's freely accessible data to obtain information on the annual number of US municipal GB issuances.³

It is noteworthy that LSEG designates government bonds as agents for government entities, and for the purposes of this study, these are duly classified and considered as government bonds altogether with sovereign GBs. Furthermore, we distinguish verified and non-verified GBs based on having a second-party opinion or not. Although certification, verification and second-party opinion are differently classified according to International Capital Market Association (ICMA) guidelines, we consider it as verified if LSEG provides a second-party opinion for GB issuance.⁴

Figure 1 illustrates the aggregated issuance amounts over time for three asset classes: corporate, municipal, and government bonds. The trend aligns with the rapid expansion of the GB market discussed earlier. Over a 14-year period, total GB issuances surged to over \$643 billion in 2021, with corporations accounting for \$407 billion (63%), government and government entities \$204 billion (32%), and municipalities \$32 billion (5%).

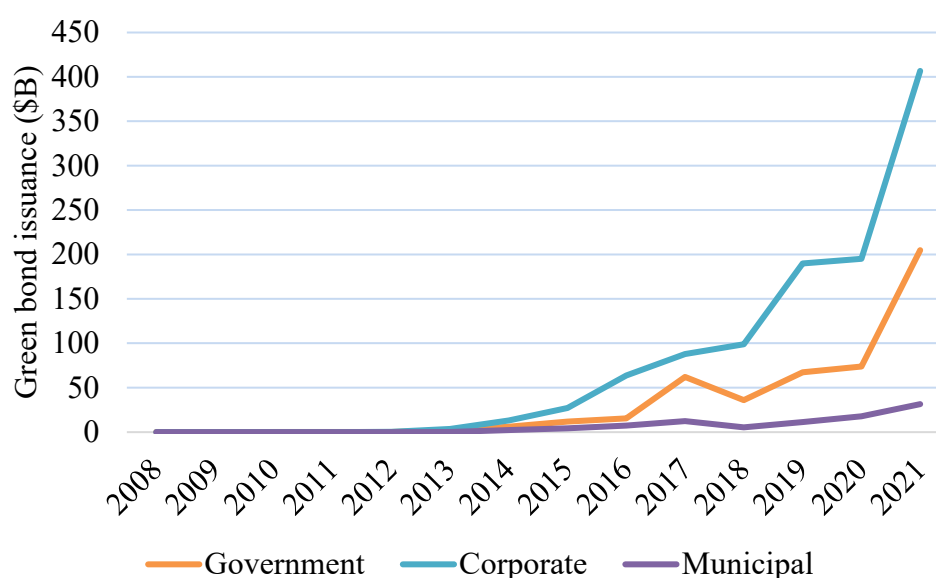


Figure 1. The amount of aggregated green bond issuances over time.

3.2. Greenhouse gases and carbon emissions

We retrieve annual GHG and CO₂ data for 182 countries from 2001 to 2022 from the Emissions Database for Global Atmospheric Research (EDGAR). Population and Gross Domestic Product (GDP) data are obtained from World Bank Open Data. After restricting the sample to countries with complete information, we construct a balanced panel of 173 countries, resulting in 3,806 observations.

³ To access: <https://www.statista.com/statistics/1289722/municipal-green-bonds-issued-usa>.

⁴ LSEG only provides data on whether GBs have a second-party opinion or not. This second-party can be external review, certification or verification. For ICMA guidelines on types of external reviews of GB: <https://www.icmagroup.org/assets/documents/regulatory/green-bonds/june-2020/external-review-guidelinesjune-2020-090620.pdf>.

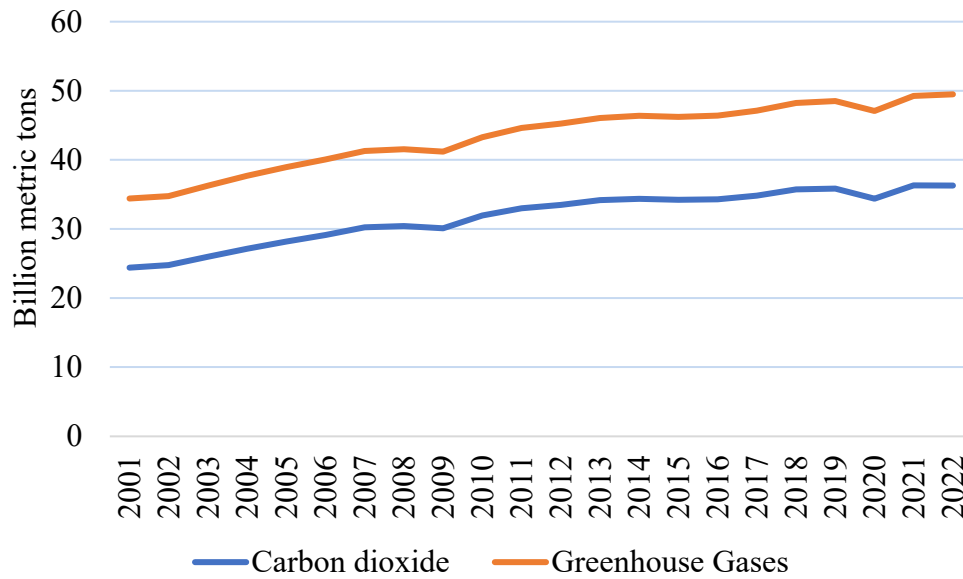


Figure 2. GHG and CO₂ emissions over time.

Figure 2 illustrates the evolution of GHG and CO₂ emissions, measured in billions of metric tons, across all countries from 2001 to 2022. Both emissions show a steady, parallel increase over time, except for a dip in 2020. Although emissions continued to rise until 2022, suggesting that GBs may have had little impact, this trend reflects data from all countries, including those without GB issuances.

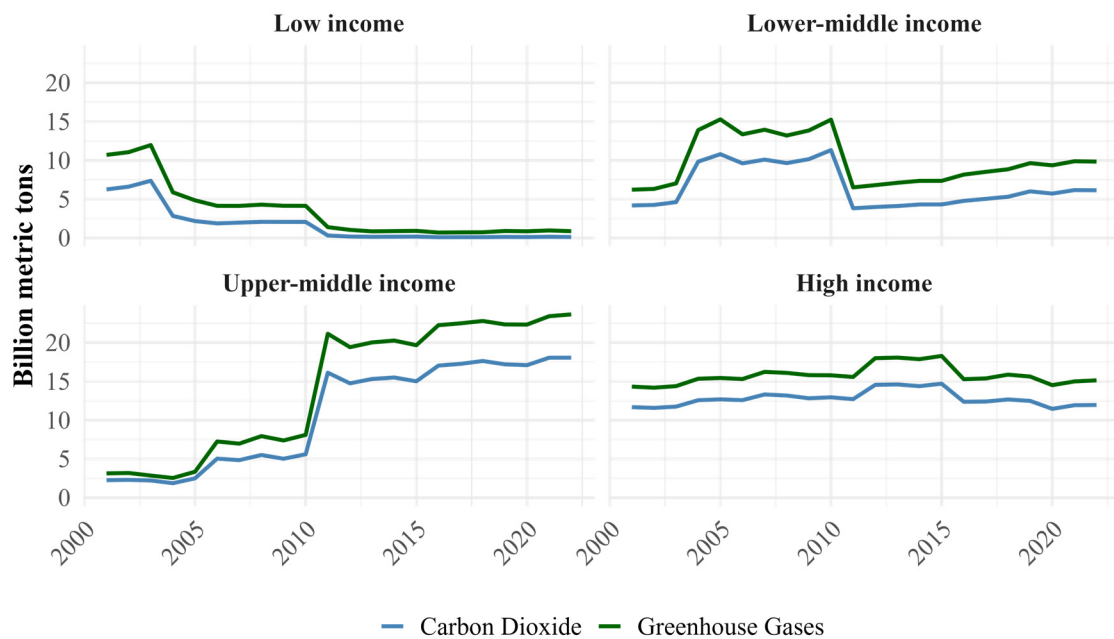


Figure 3. GHG and CO₂ emissions by income level.

We categorize countries by income level according to the World Bank's classification and present their GHG and CO₂ emissions in Figure 3.⁵ As shown in the figure, greenhouse gas emission trends differ significantly across income groups. Upper-middle-income countries have experienced nearly a sixfold increase in emissions over the period and now account for the largest share of global emissions. In contrast, low-income countries have shown a modest decline and remain the smallest contributors. Moreover, high-income countries have maintained relatively stable but persistently high emission levels.

3.3. Sovereign ESG scores

We obtain annual ESG ratings for 176 countries from LSEG covering the period from 2001 to 2022. Of these, 168 countries have complete data for all 21 years, while a country has limited 9-year ESG rating. In total, our dataset consists of 3,537 country-year observations. LSEG's methodology for calculating ESG scores is based on more than 220 indicators spanning environmental, social, and governance themes. These scores range from 0 to 100, providing a standardized assessment of government sustainability performance.⁶

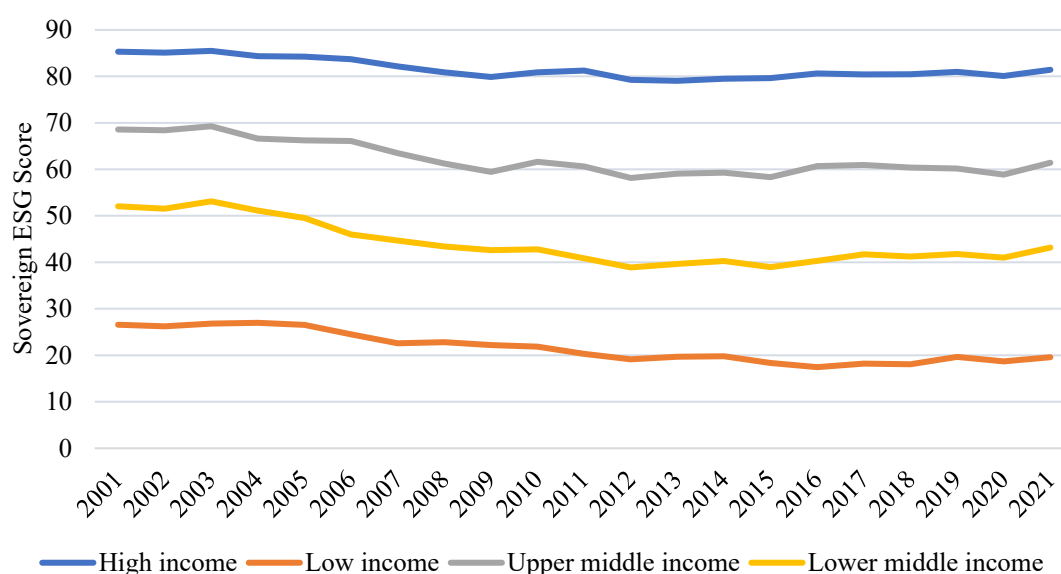


Figure 4. Trends in ESG ratings by income level across countries.

Figure 4 describes the evolution of sovereign ESG scores by income level in the 21-year span. As can be seen, ESG scores exhibit a high correlation with country wealth. Naturally, countries with higher

⁵ The World Bank classifies countries into four income groups: low, lower-middle, upper-middle, and high income. For this purpose, it uses gross national income (GNI) per capita data in U.S. dollars. To see: <https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html#:~:text=The%20World%20Bank%20classifies%20economies,%2Dmiddle%2C%20and%20high%20income.>

⁶ The methodology on calculating ESG scores is explained by the LSEG in detail here: https://www.lseg.com/content/dam/data-analytics/en_us/documents/methodology/lseg-esg-factor-in-methodology.pdf#:~:text=It%20represents%20a%20form%20of%20sustainability%20level,100%2C%20and%20defined%20by%20the%20following%20formula.

income levels often have better access to resources and institutional frameworks that facilitate the implementation of effective ESG practices. This is corroborated by the work of Gratcheva & Gurhy (2024), which highlights the high correlation of sovereign ESG scores across providers, suggesting that wealthier nations tend to have more consistent and higher ESG ratings due to their ability to invest in sustainable practices.

3.4. Descriptive statistics

Table 1 presents summary statistics for the variables used in the analysis. Panel A includes all country-year observations, while Panel B focuses on only country-year samples with GB issuances. The data suggests that higher-income countries are more likely to issue GBs, and their greenhouse gas emissions are also correlated with income levels. Additionally, countries with higher ESG scores tend to have more GB issuances, highlighting a potential link between sustainability performance and green financing.

Table 1. Descriptive statistics.

Panel A. All country-year observations (2000–2022)						
Variable	Obs	Mean	Median	Std Dev	Min	Max
Population (million)	3,806	39.51	7.75	144.84	0.01	1,428.48
GDP (\$ million)	3,806	368,356.23	24,554.81	1,520,195	63.10	23,300,000
GDP per capita (\$)	3,806	12,713.42	4,543.40	18,330.78	111.36	139,944.84
Financial Development Index (FDI)	3,806	0.32	0.24	0.23	0.00	1.00
Green bonds (\$ million)	3,806	405.489	0.00	3,354.75	0.00	73,834.34
Green bonds per capita (\$)	3,806	19.71	0.00	368.27	0.00	17,058.89
GHG emissions (millions of metric tons)	3,806	250.64	31.61	1,054.18	0.01	15,175.62
GHG emissions per capita (metric tons)	3,806	6.99	4.09	8.47	0.41	94.93
CO ₂ emissions (millions of metric tons)	3,806	183.68	11.26	851.70	0.00	12,621.61
CO ₂ emissions per capita (metric tons)	3,806	4.70	2.38	6.26	0.00	56.07
ESG score	3,537	53.44	55.67	23.81	0.00	100.00
Panel B. Country-year observations with non-zero green bond issuance						
Variable	Obs	Mean	Median	Std Dev	Min	Max
Populations (million)	289	117.92	32.55	295.40	0.33	1,428.48
GDP (\$ million)	289	1,972,531	505,000	3,962,673	5,353.47	23,300,000
GDP per capita (\$)	289	35,910.67	38,587.78	25,968.34	1,606.96	139,944.84
Financial Development Index (FDI)	289	0.63	0.66	0.19	0.20	0.93
Green bonds (\$ million)	289	5,340.12	1,251.73	11,056.55	2.66	73,834.34
Green bonds per capita (\$)	289	391.28	61.64	1,284.38	0.02	17,058.89
GHG emissions (millions of metric tons)	289	982.08	261.99	2,507.01	2.94	15,175.62
GHG emissions per capita (metric tons)	289	9.82	8.58	5.53	1.85	28.26
CO ₂ emissions (millions of metric tons)	289	767.82	190.66	2,059.59	1.85	12,621.61
CO ₂ emissions per capita (metric tons)	289	7.30	6.62	4.35	0.59	22.89
ESG score	289	77.21	81.72	12.83	35.32	100.00

This table reports summary statistics. Panel A includes all state-year observations from 2000–2022. Panel B restricts the sample to state-year observations with non-zero GB issuance.

3.5. Empirical approach

We estimate the following fixed-effects regression model to assess whether GB issuances influence GHG and CO₂ emissions:

$$\log(emissions)_{ct} = \alpha_c + \alpha_t + \alpha_t \times \alpha_r + \beta \times \log(GB_{ct-1}) + \gamma \times X_{ct-1} + \varepsilon_{ct} \quad (1)$$

where c indexes countries, t indexes years, and r represents seven regions based on World Bank classification; α_c , α_t , and $\alpha_t \times \alpha_r$ are country, year, and region by year fixed effects, respectively; $\log(emissions)$ is the natural logarithm of the metric tons of GHG and CO₂ in the country; GB is the natural logarithm of the dollar amount of GB issuance in the preceding year; X is the vector of control variables which includes $\log(population)$ and natural logarithm of GDP per capita at the country level (both lagged by one year); and ε is the error term. Since GB issuance varies at the country level, we cluster standard errors at the country level to account for potential serial correlation (Bertrand et al., 2004).

We divide our sample countries into 12 regions based on economic, political, and geographical considerations. For instance, the European Union implements unified green policies, creating similar political and regulatory impacts across its member states. This regional classification enables us to account for systematic differences in policy frameworks, economic structures, and regional interactions when analyzing the effectiveness of GBs on emissions and sovereign ESG scores. A detailed description of how the countries are assigned to each region is provided in Appendix A.

To estimate the impact of GB issuances on sovereign ESG scores, we adopt the same baseline model but replace the region fixed effects with income group fixed effects. Specifically, we include an interaction term between year and income group, allowing ESG scores to evolve over time differently across income levels. For example, ESG trends in high-income countries may improve more rapidly than in low-income countries. This relationship between income level and sovereign ESG scores has been documented by (Gratcheva et al., 2021). Thus, our model controls these group-specific time trends while estimating the effects of other variables, such as population and GDP per capita.

A key challenge with our regression model is the potential endogeneity of GB issuances. The decision to issue GBs may be correlated with unobserved factors that also influence CO₂ emissions or sovereign ESG scores. For instance, research highlights the crucial role of regulatory support in developing the GB market (Bhutta et al., 2022), while local economic conditions and environmental governance significantly impact its growth (Liu et al., 2022). Additionally, environmental regulations primarily affect CO₂ emissions through changes in industrial structure and technological progress (Zhang et al., 2021). Given this, strong eco-friendly policies in certain countries may serve as an alternative explanation for our observed negative relationship between GB issuances and greenhouse gas emissions or ESG scores.

To address this concern, we implement an instrumental variable (IV) approach as an endogeneity test, and our major results remain robust. We further conduct a placebo test by examining the effect of one-year-forward GB issuances on greenhouse gas emissions and sovereign ESG scores. The placebo test shows no reverse correlation, reinforcing the credibility of our findings and suggesting that our results are not driven by reverse causality.

4. Empirical findings

In this section, we first empirically estimate the impact of GB issuances on GHG and CO₂ emissions, followed by an analysis of their effect on sovereign ESG scores.

4.1. Empirical analysis (Green bonds and GHG & CO₂)

4.1.1. Baseline regression

Table 2 presents the major results, with Panel A and Panel B reporting estimates using GHG and CO₂ emissions as dependent variables, respectively. In Column (1), we include country and year fixed effects without the interaction term; GB issuances are found to have a significant negative association with both emissions measures. In Column (2), we add year and region fixed effects, which improves the model fit, as indicated by a higher R-squared, but reduces the magnitude of the coefficients. This suggests that part of the observed effect is explained by region-specific time trends. In Column (3) and (4), we use two-and three-year lagged GB issuances to assess the longer-term impact on emissions respectively, and the results show a similar negative relationship, consistent with the one-year lag findings. Finally, Column (5) presents the findings from the most saturated model, which includes a more extended temporal lag structure, revealing that a one-unit increase in the green bond variable is associated with a statistically significant decrease of 0.0013 and 0.0033 in the dependent variable with these persistent negative effects remaining significant across two and three-period lags in both panels.

Table 2. Correlation between GB issuances and emissions (GHG & CO₂).

	(1)	(2)	(3)	(4)	(5)
Panel A					
Log GB $t-1$	-0.0053*** (-4.88)	-0.0027*** (-2.72)			-0.0013* (-1.96)
Log GB $t-2$			-0.0030*** (-2.73)		-0.0012** (-2.04)
Log GB $t-3$				-0.0035*** (-3.03)	-0.0022*** (-2.88)
Adjusted R ²	0.55	0.62	0.62	0.62	0.62
Panel B					
Log GB $t-1$	-0.0094*** (-6.53)	-0.0055*** (-3.67)			-0.0033*** (-3.39)
Log GB $t-2$			-0.0053*** (-3.41)		-0.0021** (-2.54)
Log GB $t-3$				-0.0057*** (-3.48)	-0.0028*** (-2.86)
Adjusted R ²	0.54	0.62	0.62	0.62	0.62
Controls	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No	No
Year x Region FE	No	Yes	Yes	Yes	Yes
Observations	3,806	3,806	3,806	3,806	3,806

This table reports the empirical results from the regression specification (Equation 1), examining the impact of GB issuances on carbon emissions. *Panel A* presents estimates for GHG emissions as a dependent variable, while *Panel B* reports results for CO₂ emissions. *Log GB* is the logarithm of issue amounts of GBs. Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000–2022. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Overall, the results indicate that a 10% increase in GB issuances is associated with a reduction in GHG and CO₂ emissions of approximately 3% and 5%, respectively, over the following three years.

This finding is consistent with the literature and suggests that GBS have a sustained positive impact on emissions reduction beyond the short term.

4.1.2. Endogeneity test

Given the numerous factors that can influence greenhouse gas emissions, unobservable variables may affect our empirical findings, potentially introducing bias. To mitigate endogeneity arising from omitted variables and possible reverse causation, we adopt an instrumental variable (IV) approach. Specifically, we use the lagged average GB issuances in the same region, excluding the country's own issuances, as the instrument. Following Tian et al. (2024), we implement a two-stage least squares (2SLS) regression.

Countries within the same region face similar climate risks and policy environments, which ensures a strong correlation between the instrument and the endogenous variable, satisfying the relevance condition. Furthermore, a country's greenhouse gas emissions are primarily determined by its internal governance structure and decision-making processes, making it unlikely that GB issuances in other countries directly affect its emissions. This satisfies the exogeneity requirement for a valid instrument.

Table 3. The results of IV estimation.

	(1) Green	(2) GHG	(3) CO ₂
IV	0.0454*** (4.15)		
Log GB $_{t-1}$		−0.0329*** (−3.35)	−0.0340*** (−2.63)
Controls	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	3,806	3,806	3,806
Kleibergen–Paap Wald rank F statistic	61.89		
Wu-Hausman Test		78.46	25.72

This table reports the regression result of instrumental variable (IV) estimation, IV is the lagged average green bond issuances in the same region, excluding the country's own issuances, and other control variables are same as above. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

The results in Column (1) of Table 3 indicate a significant positive relationship between the IV and GB issuances. Moreover, the F-statistic value of 61.89 suggests that there is no weak instrument problem. These results support the validity of our IV, confirming that GB issuance trends in neighboring countries promote green bond issuance within a given country. More importantly, Columns (2) and (3) show that the negative effect of GBs on greenhouse gas emissions remains significant. Since the number of proxy variables equals the number of IVs, overidentification is not a concern. Overall, our major findings remain robust and significant even after accounting for potential endogeneity.

4.1.3. Robustness test

We conduct several robustness tests in Table 4. In Column (1), we conduct a placebo test by replacing lagged green issuances with one-year leads. The rationale is that future issuances of GBs should not influence current greenhouse gas emissions or sovereign ESG scores; therefore, any significant effect would suggest potential reverse causality or omitted variable bias. As shown, both Panel A and Panel B report insignificant coefficients for the one-year lead variable (−0.0017 and −0.0041, respectively), with t-statistics below conventional significance levels. These results confirm that our major findings are not driven by reverse causality and strengthen the robustness of our empirical strategy.

Table 4. Robustness tests.

	(1) Placebo	(2) Green Per Capita	(3) Carbon Intensity	(4) Sub-Period (2010-2022)
Panel A				
Log GB $_{t-1}$	−0.0017 (−1.43)		−0.0019* (−1.73)	−0.0017** (−2.24)
GB per capita $_{t-1}$		−0.0102*** (−3.71)		
Adjusted R ²	0.62	0.62	0.34	0.37
Panel B				
Log GB $_{t-1}$	−0.0041 (−1.62)		−0.0019** (−2.07)	−0.0038*** (−3.66)
GB per capita $_t$		−0.0135*** (−3.03)		
Adjusted R ²	0.62	0.62	0.27	0.41
Controls	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Year x Region FE	Yes	Yes	Yes	Yes
Observations	3,633	3,806	3,806	2,076

This table reports the results of the robustness regressions. *Panel A* presents estimates for GHG emissions as a dependent variable, while *Panel B* reports results for CO₂ emissions. *Log GB* refers to the logarithm of GB issuance amounts, while *GB per capita* is the total green bond issuance (in \$1000) divided by population. Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000–2020. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

In Column (2), we replace the logarithm of GB issuances with GB issuance (in \$1,000) per capita. This specification accounts for differences in country size and population, enabling us to test whether the relationship between GB issuance and emissions reduction holds when scaled by population. It also helps address potential bias from logging zero issuance amounts, which requires adding a small constant and can introduce measurement error. The results show that the issuance of \$1,000 of GBs per capita is associated with a subsequent decrease in GHG and CO₂ emissions by 1% and 1.3%, respectively.

In Column (3), as an additional robustness test, we replace the dependent variable from the logarithm of total carbon emissions with carbon intensity (measured as CO₂ emissions relative to GDP). This measure accounts for the scale of economic activity and captures the efficiency of emissions relative to output. The results that GB issuances are associated with a significant reduction in carbon intensity, with coefficients of −0.0019 ($t = -1.73$) and −0.0019 ($t = -2.07$) across specifications. These

findings indicate that the negative effect of GBs holds not only in absolute emissions but also when normalized by economic activity.

Finally, in Column (4), to address potential bias from the early years when GB markets were virtually inactive, we exclude observations prior to 2010; the period during which GB issuances were nearly zero. This restriction helps ensure that the analysis focuses on years with meaningful variation in GB activity. While the estimated effects show a slight decrease in magnitude, the results remain statistically significant, confirming the robustness of our main findings.

4.1.4. Sensitivity analysis

In this subsection, we conduct a series of sensitivity analyses, with the results summarized in Table 5. Prior studies suggest that GBs are generally effective in major carbon-emitting countries; however, their success tends to be significantly enhanced by stronger institutional frameworks, which are more common in high-income nations (Tolliver et al., 2020). Additionally, (Czech et al., 2023) report varying levels of effectiveness across Central and Eastern European (CEE) countries, with outcomes largely influenced by economic stability and governance quality. Building on these insights, we first examine whether the impact of GB issuances differs by country income level.

Our analysis reveals that green bonds are significantly more effective at reducing emissions in higher-income countries (Column (1)). To understand the mechanism behind this finding, we investigate the role of financial development.

The results in Column (2) suggest that financial development is a key channel explaining this effect. High-income economies are characterized by more mature and sophisticated financial markets. Our finding that the effectiveness of green bonds is amplified in countries with a higher Financial Development Index (FDI)⁷ provides a direct explanation for the income-based results.

These advanced financial systems are better equipped to translate green bond proceeds into environmental outcomes by ensuring efficient capital allocation to viable green projects, enforcing greater transparency, and minimizing the risks of greenwashing through robust oversight. Therefore, the enhanced impact of green bonds in high-income nations is not due to income, but rather to the well-developed financial infrastructure that typically accompanies it.

Furthermore, we examine whether the effectiveness of GBs differs between those with an external review and those without. The prior study shows that certification improves the effectiveness of green bonds (Fatica & Panzica, 2021; Flammer, 2023). In our sample, Refinitiv provides information on whether GBs have undergone an external review, which may take the form of certification, verification, or a third-party opinion. In the final three columns, we test the hypothesis that externally verified green bonds are more effective at reducing emissions by mitigating the risks of greenwashing. Furthermore, we further show that this effect is conditional on the country's level of financial development, as robust financial systems enhance transparency and accountability.

⁷ A composite measure by the IMF capturing the depth, access, and efficiency of financial institutions and markets (Svirydzenka, 2016).

Table 5. Heterogeneity tests.

	Income Level Impact		External Review Impact		
	(1)	(2)	(3)	(4)	(5)
	Interaction	FDI	Baseline	Above FDI	Below FDI
Panel A					
Log GB $_{t-1}$	0.0105** (2.39)	0.0069*** (3.17)			
Income Group	−0.0062 (−1.47)				
Log GB x Income Group	−0.0038*** (−2.98)				
FDI $_{t-1}$		0.1821*** (3.27)			
Log GB x FDI		−0.0159*** (−4.31)			
Log Verified GB $_{t-1}$			−0.0021*** (−2.74)	−0.0021** (−2.36)	−0.0135** (−2.15)
Log Non-verified GB $_{t-1}$			−0.0019* (−1.95)	−0.0014 (−1.65)	−0.0071** (−2.41)
Adjusted R ²	0.62	0.63	0.62	0.63	0.60
Panel B					
Log GB $_{t-1}$	0.0211*** (4.64)	0.0232 (0.70)			
Income Group	−0.0045 (−0.44)				
Log GB x Income Group	−0.0084*** (−6.63)				
FDI $_{t-1}$		0.2732*** (2.74)			
Log GB x FDI		−0.0213** (−2.41)			
Log Verified GB $_{t-1}$			−0.0036** (−2.57)	−0.0023** (−2.10)	−0.0205*** (−2.83)
Log Non-verified GB $_{t-1}$			−0.0038*** (−3.14)	−0.0016* (−1.77)	−0.0129* (−4.98)
Adjusted R ²	0.62	0.63	0.62	0.63	0.63
Controls	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Year x Region FE	Yes	Yes	Yes	Yes	Yes
Observations	3,806	3,806	3,806	1,955	1,851

This table presents the results of sensitivity analyses. *Panel A* presents estimates for GHG emissions as a dependent variable, while *Panel B* reports results for CO₂ emissions. *Log GB* refers to the logarithm of GB issuance amounts. Income Group is a numerical variable indicating a country's income level, categorized from 1 (low income) to 4 (high income). *FDI* is an index ranging from 0 (least developed) to 1 (most developed). *Log Verified Green* and *Log Non-verified Green* are the logarithm of GB issuance amounts with external review and without, respectively. Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000–2022. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

The results in Column (3) show that verified and non-verified bonds reduce emissions. This might suggest the little role of verification or high level of greenwashing.

Columns (4)–(5) split the sample by the Financial Development Index. In high-FDI countries, verified bonds maintain a significant negative impact on emissions, whereas non-verified bonds lose

significance, highlighting the role of verification in advanced financial markets. In low-FDI countries, verified and non-verified bonds show strong, significant emission reductions, suggesting that in less-developed markets, simply providing green capital is sufficient to generate substantial environmental impact, with verification adding incremental value.

Overall, these results indicate that verification matters most in well-developed financial systems, while in lower-development contexts, the availability of green financing itself drives emissions reductions, which is consistent with economic intuition given the scarcity of green capital in these markets.

4.2. Empirical analysis (Green bonds and sovereign ESG scores)

4.2.1. Baseline model

In this subsection, we examine the impact of GB issuances on sovereign ESG scores. The baseline regression results are presented in Table 6. In Column (1), where we control for country and year fixed effects, the coefficient for GB issuance is positive but not significant. In Column (2), we further refine the model by including interactions between year and income group fixed effects, along with country fixed effects. The coefficient strengthens, and the results suggest that a 10% increase in GB issuance is associated with an approximate one-point rise in the ESG score, significant at the 1% level. In Column (3) and (4), we assess the impact of GB issuances with a two-and three-year lag, which reveals a significant and positive association in a declining impact.

Table 6. Green bonds and sovereign ESG scores.

	Dependent variable: Sovereign ESG Score				
	(1)	(2)	(3)	(4)	(5)
Log GB $t-1$	0.040 (1.06)	0.107*** (2.95)			0.079*** (3.25)
Log GB $t-2$			0.099*** (2.68)		0.051*** (2.75)
Log GB $t-3$				0.078** (2.02)	0.001 (0.34)
Controls	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No	No
Year x Income Group FE	No	Yes	Yes	Yes	Yes
Adjusted R ²	0.60	0.62	0.62	0.62	0.62
Observations	3,537	3,537	3,537	3,537	3,537

This table presents the empirical results of the baseline regressions examining the impact of GB issuances on sovereign ESG scores. *Log GB* refers to the logarithm of GB issuance amounts. Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000-2022. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Finally, we evaluate the cumulative impact of GB issuance over a three-year period on the current sovereign ESG score in Column (5). The result shows that the positive effect of green bonds on a

country's ESG score shows signs of fading after two years. This seems meaningful as annual ESG scores should typically demonstrate present sustainability picture of a country.

Overall, the results indicate that GB issuances are positively associated with sovereign ESG scores, with the strongest effects observed within one to two years after issuance. The impact gradually diminishes over time, reflecting the fact that annual ESG scores primarily capture the current sustainability performance of a country (Crifo et al., 2017).

4.2.2. Endogeneity test

In a similar way to Section 4.1.2., we employ an IV approach to mitigate the possible endogeneity issue in this sub-section. As above, we use the lag average GB issuances in the same region, excluding the country's own issuances. We believe that a country's ESG score is largely shaped by its own governance and decision-making, making it unlikely that GB issuances in other countries directly influence its rating. This satisfies the exogeneity requirement, supporting the validity of the instrument.

Table 7 presents the results of the IV estimation. The F -statistic value of 17.87 indicates that there is no weak instrument problem. Column (1) confirms that GB issuance trends in neighboring countries positively influence issuance within a given country. More importantly, Column (2) shows that the positive effect of GBs on sovereign ESG scores remains significant. As the number of proxy variables equals the number of IVs, overidentification is not a concern. Overall, these results demonstrate that our major findings are robust and hold even after addressing potential endogeneity.

Table 7. The results of IV estimation.

	(1) Green	(2) ESG
IV	0.0271*** (4.07)	
Green _{<i>t-1</i>}		0.556** (2.04)
Controls	Yes	Yes
Country FE	Yes	Yes
Year x Income Group FE	Yes	Yes
Observations	3,537	3,537
Kleibergen–Paap Wald rank F statistic	17.87	
Wu-Hausman Test	3.46	

This table reports the regression result of instrumental variable (IV) estimation, IV is the lagged average green bond issuances in the same region, excluding the country's own issuances, and other control variables are the same as above. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

4.2.3. Robustness test

Table 8 presents the results of the robustness regressions. In Column (1), we conduct a placebo test by replacing lagged GB issuances with one-year leads. The coefficient remains positive but is not statistically significant, confirming that our main results are not driven by reverse causality and further reinforcing the robustness of our empirical strategy.

Table 8. Robustness checks.

	Dependent variable: Sovereign ESG Score					
	Placebo	Sub-Period (2010–2020)	Green Per Capita		Green Intensity	
	(1)	(2)	(3)	(4)	(5)	(6)
Log GB $_{t-1}$	0.054 (1.41)	0.068*** (2.72)				
GB per capita $_{t-1}$			0.069 (0.45)	0.002* (1.79)		
Income Group				−0.204 (−0.75)		−0.207 (−0.77)
GB per capita x Income Group				−0.001** (−1.99)		
GB intensity $_{t-1}$					0.011 (1.18)	0.147*** (2.70)
GB intensity x Income Group						−0.045*** (−2.77)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	Yes	No	Yes
Year x Income Group FE	Yes	Yes	Yes	No	Yes	No
Adjusted R ²	0.60	0.46	0.61	0.60	0.61	0.60
Observations	3,537	1,857	3,537	3,537	3,537	3,537

This table reports the results of the robustness regressions. *Log GB* refers to the logarithm of GB issuance amounts. *GB per capita* is the total green bond issuance (in \$1000) divided by population, while *GB intensity* is the total green bond issuance divided by GDP. *Income Group* is a numerical variable indicating a country's income level, categorized from 1 (low income) to 4 (high income). Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000–2022. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

We re-estimate our regression by focusing on a subgroup of observations, specifically those after 2010, the period following the emergence of major GB issuances in Column (2). This approach helps isolate the impact of potential bias introduced by the presence of many zero issuances in the earlier years, which could distort the results. By restricting the sample to years with more significant GB activity, we aim to obtain a clearer picture of the relationship between GB issuances and the dependent variable. The result remains robust, though with a slight decline in the coefficient, reducing from the original value to 0.068.

In Column (3), we replace the logarithm of the GB amount with GB per capita (in \$1000) to account for country size, arguing that the absolute volume of green bonds is more economically meaningful when scaled by population. While the coefficient for GB per capita is positive, it is not statistically significant, suggesting that, after adjusting for population size, the relationship between GB issuances and the outcome variable remains weak or inconsistent possibly due to the economic and ecological disparities (Sarwar et al., 2024). Therefore, we include interaction term with income group in Column (4). However, the results show a significant negative moderation, indicating that GB issuance per capita has stronger positive effects in lower-income countries than in higher-income ones. This seems logical, as wealthier economies may already have saturated markets or higher baseline ESG scores, leaving less room for marginal gains.

In Columns (5) and (6), we turn to GB intensity (issuance relative to GDP), which reflects the bond market's weight within the national economy. Similar to the per capita specification, the baseline

effect in Column (5) is insignificant. Column (6) reveals a positive main effect for intensity alongside a significant negative interaction with income group. This suggests that a more substantial GB market boosts ESG outcomes, but the effect diminishes in higher-income countries, consistent with diminishing returns or higher initial ESG levels. That both scaling approaches yield the same conditional pattern offers heterogeneous impact of GB issuances.

Overall, the robustness tests confirm the stability of our major findings. However, alternative specifications using per capita and GDP-scaled measures further demonstrate that the ESG impact of green bonds might be conditional systematically varying with countries' income levels and hence, we further measure this correlation in our sensitivity analysis in the next subsection.

4.2.4. Sensitivity analysis

Table 9. Heterogeneity analysis.

	Dependent variable: Sovereign ESG Score				
	Income Level Impact		External Review Impact		(5) Prior ESG
	(1) Interaction	(2) FDI	(3) Baseline	(4) FDI	
Log GB $_{t-1}$	0.659*** (4.12)	0.221*** (3.24)			
Income Group	-0.208 (-0.77)				
Log GB x Income Group	-0.171*** (4.20)				
FDI $_{t-1}$		4.24* (1.84)		4.32* (1.87)	
Log GB x FDI		-0.279*** (3.13)			
Log Verified GB $_{t-1}$			0.043 (1.46)	0.277*** (3.22)	0.238*** (3.40)
Log Non-verified GB $_{t-1}$			0.089*** (2.93)	0.157*** (2.64)	-0.126* (-1.69)
Log Verified GB x FDI				-0.343*** (-2.93)	
Log Non-verified GB x FDI				-0.103 (1.20)	
ESG $_{t-2}$					0.732*** (20.77)
Verified Green x ESG					-0.003*** (-2.82)
Non-verified Green x ESG					0.002** (2.15)
Controls	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	No	No	No
Year x Income Group FE	No	No	Yes	Yes	Yes
Adjusted R ²	0.60	0.60	0.62	0.63	0.63
Observations	3,537	3,537	3,537	3,537	3,199

This table presents the results of sensitivity analyses. *Log GB* refers to the logarithm of GB issuance amounts. Income Group is a numerical variable indicating a country's income level, categorized from 1 (low income) to 4 (high income). *FDI* is an index ranging from 0 (least developed) to 1 (most developed). Log Verified Green and Log Non-verified Green are the logarithm of GB issuance amounts with external review and without, respectively. Control variables include the one-year lagged logarithms of population and GDP per capita at the country level. The unit of observation is a country-year, spanning the period 2000-2022. T-statistics shown in parentheses are clustered at the country level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

In this subsection, we conduct two sensitivity analyses, with the results reported in Table 9. We focus on the impact of GB issuances on sovereign ESG scores, accounting for country income levels and bond certification status. We hypothesize that GBs are likely to have a stronger effect on the ESG scores of developing or lower-income countries due to their signaling role. Additionally, we expect verified GBs to exert a greater influence than non-verified bonds, reflecting their higher credibility and reduced risk of greenwashing (Ghitti et al., 2023).

In Column (1), we introduce an interaction term between the logarithm of GB issuances and income level, where income is coded numerically from 1 (low income) to 4 (high income). The results show that the main effect of GB issuances remains positive and highly significant, confirming their robust contribution to sovereign ESG scores. However, the interaction term is negative and significant, indicating that the positive impact of GB issuances on ESG scores diminishes as income levels increase. This suggests that the beneficial effects of GB issuance on sovereign ESG performance are more pronounced in lower-income countries and tend to weaken in higher-income economies. This pattern aligns with our expectations and is consistent with the financial development channel. In Column (2), we replace income level with the Financial Development Index, and the results corroborate this finding, showing a significant negative interaction between green bonds and FDI.

We then examine the impact of external verification on sovereign ESG scores and the moderating roles of financial development and past ESG performance. We include interactions between verified/non-verified green bonds and the Financial Development Index to test the hypothesis that verification matters more in countries with less-developed financial markets, where credibility signals are most valuable.

The results show that the effectiveness of green bonds is strongly moderated by a country's financial and sustainability context, explaining the apparent insignificance of verified bonds in the baseline model (Column (3)). While non-verified bonds consistently exhibit a positive effect, the impact of verified bonds is conditional. In Column (4), FDI emerges as a significant negative moderator for verified bonds, suggesting that in highly developed financial markets, with strong oversight and ample green investment opportunities, the additional value of third-party verification is limited. Column (5) highlights the role of prior ESG performance: The high persistence of ESG scores dominates the model, and the negative interaction with verified bonds indicates that in countries with already high ESG ratings, verification might provide little incremental information. In contrast, the positive and significant interaction for non-verified bonds suggests that they have greater impact in lower-ESG contexts, where any green signal is notable. These findings indicate that the insignificance of verified bonds in simpler models reflects the contextual dependence of their effect rather than inefficacy.

Overall, the heterogeneity results strongly support the core hypothesis that context matters. The positive impact of green bonds is significantly stronger in lower-income countries and those with less-developed financial markets, as shown by the negative and significant interactions with income level and the Financial Development Index. This supports the view that green bonds act as a potent signal where sustainable finance is relatively novel. While non-verified bonds exhibit a consistent baseline effect, the influence of external verification is highly conditional: In financially advanced countries or those with already-high ESG scores, verification adds little marginal value, whereas it is most effective where credibility is scarce. These findings underscore that green bond efficacy is not uniform but shaped by a country's economic and sustainability context.

5. Conclusions

In this paper, we evaluate the effectiveness of GB issuances by estimating their impact on GHG emissions and sovereign ESG scores. The findings suggest that GB issuances are correlated with a reduction in both GHG and CO₂ emissions in the years following issuance. Furthermore, a country's level of financial development plays a parallel role, with more developed financial systems enhancing the impact of GBs on carbon reduction.

Additionally, our results show that GBs are associated with subsequent improvements in sovereign ESG scores. The heterogeneity analysis further reinforces this conclusion, demonstrating that the positive impact of green bonds is strongest in lower-income countries and those with less-developed financial markets, where green finance is relatively novel. Non-verified bonds exhibit a consistent baseline effect, while the effectiveness of verified bonds depends on financial development and prior ESG performance, being most impactful in contexts where credibility is scarce. Overall, these findings highlight that the efficacy of green bonds is context-dependent, shaped by a country's economic structure, financial sophistication, and sustainability trajectory.

Our paper offers two important implications. First, GB issuances appear to be an effective tool for reducing greenhouse gas emissions and improving sovereign ESG scores. This suggests that expanding GB markets in developing economies could deliver substantial environmental and sustainability gains. Second, strengthening financial systems is a climate strategy, as higher financial development amplifies the emission-reduction effects of GB.

In conclusion, our analysis advises against a one-size-fits-all approach to green bond policy. The most effective strategies will be those that are carefully tailored to a country's income level, financial development, and existing sustainability trajectory to maximize the tangible environmental and financial returns of their sustainable finance markets.

There are a few limitations to this study. First, our analysis relies on ESG scores from a single provider. Given that ESG assessment methodologies vary across data providers, the results may differ when using alternative ESG measures. Second, our classification of external reviews for GB groups together various types of verification. Disaggregating these review types in future studies could offer more nuanced insights into their specific effectiveness. Addressing these limitations could help deepen understanding of the true impact of GBs on sovereign sustainability performance.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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