Climate Change Risk and Green Bond Pricing

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Abstract

We examine whether and how materializations of climate change risk affect green bond prices. Green bonds exhibit a decrease in yield relative to brown bonds after a natural disaster and the magnitude of this variation increases with disaster severity. This is consistent with disasters strengthening investor demand for green assets that are better hedged against climate change risk. We then examine whether the post-disaster reaction is rational or affected by a behavioral bias. A significant fraction of the impact of disasters on green bond prices is temporary, and this impact grows weaker when disasters become more repetitive. The evidence is consistent with the presence of both a rational and a behavioral component: while part of the price response is persistent, most of it is driven by investor overreaction that fades as disasters become less salient.

Keywords: green bond, climate change risk, natural disasters, behavioral finance.

JEL Classification: G12, G41.

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1. Introduction

Climate change is increasingly considered as one of the major challenges of our time. International agreements, regulatory proposals, and academic contributions are fueling the debate about the consequences that climate change may generate on the broader economy. Analysts estimate that the world economy may lose up to 18% GDP if no action is taken (Guo et al., 2021). In financial markets, climate change is now clearly recognized as a risk source that affects asset prices. Theoretical studies are attempting to incorporate investor concerns towards climate change in asset pricing models (Pedersen et al., 2021; Pástor et al., 2021). At the same time, empirical evidence documents that various dimensions of such risk are found to impact both equity (e.g., Engle et al., 2020) and bond (e.g., Painter, 2020) returns.

A fundamental question is whether climate change risk is correctly priced as distortions may undermine market informativeness and lead to an inefficient allocation of capital that leaves economic activities vulnerable to the impact of climate change. A major challenge to addressing this question is to measure asset exposure. The literature has made several attempts to proxy for climate risk, such as relying on carbon intensity or environmental rating measures (e.g., Bolton and Kacperczyk, 2021). We believe that the bond market is a well suited empirical setting for this purpose because of the presence of green bonds, namely securities whose proceeds are exclusively allocated to climate-related or environmental projects. By factoring in the risk that climate change can materially affect financial performance, green bonds benefit from a reduced exposure to climate risk relative to their brown counterparts (Cepni et al., 2022). Thus, adverse climate shocks strengthen investors' preference for green assets as they are better hedges against materialization of climate change risk (Pástor et al., 2021). This implies diverging price reactions of green and brown bonds to unexpected climate-related events. Our purpose is to investigate the accuracy of these price reactions.

We identify two, non-mutually exclusive explanations for the price reaction of green and brown bonds to adverse climate shocks. If a climate shock signaled a rise in real climate change risk, then the return required by investors would rationally increase with the risk exposure of an asset. As long as green bonds are better hedged against climate change risk than brown bonds, green bonds will outperform brown bonds when concerns about climate change increase unexpectedly. We call this the rational explanation. At the same time, we consider the possibility that investors misestimate climate change risk. Mispricing may arise from human behavioral biases that affect the collection and processing of financial information, resulting in irrational investment decisions (Shefrin and Statman, 1994). One of such biases consists in individuals overreacting to unexpected and dramatic news events (De Bondt and Thaler, 1985). In our context, investors may overreact to climate-related shocks because this type of events triggers an upward shift in their perception of climate change risk even if the real risk does not change. We call this the behavioral explanation.

To assess which of the rational and behavioral explanations plays a larger role, we focus on two pricing attributes on which they generate conflicting predictions. A first key difference in their implications is associated with the persistence of the effect of climate shocks on bond prices. If diverging reactions of green and brown bonds are due to rational differences in the risk compensation required by investors, then this price effect is permanent because these events have conveyed new information about climate change risk. If, on the other hand, investors overweight the probability of a climate-related shock in the immediate aftermath of the event but correct this bias as the salience of the event decreases over time, then the price effect is temporary because the emotional impact of the shock fades away with time. We therefore test whether the effect is persistent or temporary. A second key difference in the implications generated by the two explanations is associated with event novelty. While the rational explanation implies that the price responses of green and brown bonds reflect their different risk exposures, the behavioral explanation predicts that these responses grow weaker when the salience of the event decreases as climate-related shocks repeat. We therefore test whether this effect weakens when climate-related events become less unusual.

As a source of shock to climate change risk, we employ natural disasters as they are exogenous to bond characteristics and prices and provide us with a clean identification strategy based on using brown bonds issued in the same country and, when possible, by the same issuer as a control group. Our sample is composed of 1,972,974 bond-month observations related to 48,476 bonds traded worldwide during the period 2015-2022, for which we obtain secondary market data from Refinitiv. We employ two disaster variables, namely the percentage of affected population in the country where the event occurs, and a large-scale disaster dummy which identifies events belonging to the top 1% of the distribution in terms of percentage of affected people in a country, similar to Cavallo et al. (2013). We focus on the secondary market because of the endogenous nature of the decision to issue a bond, which is likely to be correlated with the occurrence of natural disasters, thereby causing selection bias in primary market data.

We start our empirical analysis by investigating whether the occurrence of a natural disaster causes a decrease (increase) in green bond yields (prices) relative to brown bonds and whether this effect is more pronounced after the occurrence of more severe disasters. We find that green bond yields decrease relative to those of brown bonds by an economically relevant amount after the occurrence of a natural disaster in the bond's country of issue, and the magnitude of this variation increases with disaster severity. In economic terms, we find that a one percentage point increase in a country's affected population leads to an average 2.6 basis points widening in the brown-green yield spread. Our difference-in-differences model documents a relative decrease in green bond yields of 31-34 basis points after the occurrence of a large-scale disaster, which amounts to approximately a third of the average brown-green yield spread.

As long as unexpected climate-related events strengthen investors' preference for green assets, the channel through which this shift in preference affects bond prices is the increased demand for green bonds. To document this channel, we show that green bonds exhibit a relative increase in liquidity after the occurrence of a natural disaster, with this effect being larger in magnitude after more severe events. Combined with a simultaneous increase in green bond prices relative to brown bonds, results are consistent with green bonds experiencing stronger demand. We also document the following cross-sectional pattern that corroborates the above findings. Green bonds that are perceived to be better positioned against climate change risk within the green bond population (i.e., "greener" bonds) should be particularly sought after by investors in the aftermath of a disaster. Consistently, we find that the magnitude of the post-disaster widening in the yield spread between brown and green bonds increases with the issuer's environmental score.

We then disentangle the role played by the rational and behavioral explanations. First, we test whether the disaster-induced effect on bond prices is persistent or temporary, and find that a significant component of this effect is temporary. The widening in the brown-green yield spread amounts to 60 basis points in the month following the occurrence of a large-scale disaster and reduces to 13 basis points six months later, equaling a 78% decrease. This suggests that the price impact of natural disasters is primarily driven by investors overestimating climate change risk, as most of the post-disaster reaction is reabsorbed when event saliency decreases. At the same time, the disaster-induced effect does not completely disappear, which indicates that new information about increased climate change risk is persistently incorporated into prices. Second, we test whether the relative decrease in green bond yields becomes less pronounced after repeated disasters, and find empirical support to this prediction. This is consistent with a weaker overreaction by investors when disasters become less unusual and therefore less salient, consistent with the presence of a behavioral effect. Overall, the evidence shows that bond prices persistently adjust to new information conveyed by natural disasters, but the immediate post-disaster effect is exacerbated by investors' overreaction.

Finally, we rule out three possible alternative explanations to our results. First, the variation in green bond yields may be due to an unobserved shock to the green bond market of multiple countries, such as a regional regulatory intervention occurring in the same month as a disaster. We estimate a triple difference model to benchmark the behavior of green bond yields not only against that of brown bonds in the same country but also against that of bonds traded in unaffected countries. Results are confirmed. Second, the relative decrease in green bond yields may be due to the fact that green bond issuers (and not just green bonds) are perceived as being less risky relative to brown issuers after a natural disaster. This implies a homogeneous price impact on all debt securities of green bond issuers, which we do not find. Third, the physical damage suffered by the issuer's assets following a disaster may drive our results. We therefore conduct a test on the subsample of foreign bonds that allows to identify the price reaction to disasters occurring in the bond's country of issue, which does not correspond to the issuer's home country. The evidence is robust.

The paper proceeds as follows. Section 2 reviews the related literature, outlines the contribution of this study, and formulates the testable hypotheses. Section 3 presents our empirical design. Section 4 provides evidence of the different reaction of green and brown bond prices to natural disasters. Section 5 tests the rational and behavioral explanations for this effect. Section 6 addresses possible alternative explanations by presenting results of additional tests. Section 7 concludes.

2. Related Literature and Hypotheses

2.1 Related Literature and Contribution

Our study contributes to a burgeoning climate finance literature that examines the asset pricing implications of climate change risk (see Giglio et al. (2021) for a review). Two different approaches have developed within this stream of literature. The first approach models climate change as a new systematic risk factor and investigates the extent to which it is priced into financial assets. The systematic nature of climate change risk is motivated by investors' preference for environmentally friendly assets (e.g., Pedersen et al., 2021) as well as economic activities' exposure to transition risk arising from environmental policy uncertainty (Hsu et al., 2023). Theoretical modeling and empirical evidence on both equity (e.g., Ardia et al., 2022) and debt (e.g., Huynh and Xia, 2021a) markets is extensive. In the bond market, a growing stream of literature has documented a price premium for green bonds relative to otherwise identical brown bonds, a phenomenon also known as "greenium" (e.g., Baker et al., 2022). Goldsmith-Pinkham et al. (2023) and Painter et al. (2020) document how climate change risk affects U.S. municipal bond prices.

The second approach, to which this paper is closely related, examines how financial markets react to the occurrence of extreme climate-related events. A number of studies document behavioral mechanisms that lead individuals to temporarily misestimate climate risk after such events. With respect to equity markets, Hong et al. (2019) find that food stock prices underreact to drought risk, and Lanfear et al. (2019) document abnormal effects of hurricanes on stock returns and liquidity. As for managerial decisions, Dessaint and Matray (2017) show that managers overreact to natural disasters by abnormally increasing cash holdings, while Alok et al. (2020) document that fund managers underweight disaster zone stocks. Far less attention has been devoted to how bond markets react to these events, with a few exceptions: Huynh and Xia (2021b) find that, when a U.S. firm is exposed to a disaster, its bond and stock prices decrease, causing future returns to be higher; Auh et al. (2022) document that natural disasters substantially reduce U.S. municipal bond returns.

We contribute to the literature in three ways. First, we advance the knowledge on the asset pricing of climate change risk. Specifically, while most of the evidence is based on equity securities and models climate change as a systematic risk source, we shed light on how behavioral mechanisms lead to a temporary misestimation of such risk and affect bond prices. Second, we take advantage of the presence of green bonds and generate diverging pricing implications relative to brown bonds based on their different exposure to climate change risk. The green bond market is fast growing and rapidly evolving, which calls for a deeper investigation of its pricing patterns. To this extent, we advance our understanding by unveiling both a rational and a behavioral component in the price reaction to extreme climate-related events. Third, this is a comprehensive study on how investors estimate climate change risk following natural disasters focusing not only in the U.S. bond market but worldwide.

2.2 Testable Hypotheses

We hypothesize that green and brown bond prices exhibit different patterns following the occurrence of a disaster. Like climate change realizations negatively affect the value of coastal real estate exposed to sea level rise and positively affect inland regions (Giglio et al., 2021), green and brown bond prices react differently to extreme climate-related events due to their different exposure to climate change risk. Consistent with green assets providing investors with a better climate risk hedge than brown assets (Pástor et al., 2021), green bonds benefit from a reduced exposure to climate risk relative to their brown counterparts (Cepni et al., 2022). We therefore expect green bond yields (prices) to decrease (increase) relative to brown bonds after the occurrence of a natural disaster. Also, this effect should be more pronounced after the occurrence of more severe disasters.

Hypothesis 1. Green bond yields decrease relative to brown bond yields after the occurrence of a natural disaster, and the magnitude of this effect increases with disaster severity.

The above hypothesis is consistent with both a rational and a behavioral explanation. To assess which effect plays a larger role, we focus on two characteristics of the price impact of natural disasters on which the rational and behavioral explanations generate contradictory implications. The first one is persistence. The rational explanation implies that disasters signal an increase in real climate change risk which is correlated with the severity of the event, which pushes investors to require a higher risk premium for brown bonds due to their increased risk exposure relative to green bonds. Thus, this explanation predicts a persistent effect of natural disasters on bond prices. On the other hand, salience theories of choice imply that investors react to a salient left-tail event in an overly risk-averse manner because they temporarily overweight its probability (Tversky and Kahneman, 1973; Bordalo et al., 2012). Thus, an unexpected worsening of the climate, which in our setting takes the form of a natural disaster, causes an upward shift in climate change risk perception that strengthens investors' preference for green assets, thereby increasing the demand for green bonds relative to brown bonds. Since, however, this does not imply any change in the real risk, the overreaction fades as time goes by and the emotional intensity and vividness of the event subsides. In other words, the disaster-induced effect reabsorbs when the salience of the event decreases, which generates the prediction that the relative decrease in green bond yields is temporary. We therefore formulate the following two conflicting hypotheses:

Hypothesis 2a. The relative decrease in green bond yields after the occurrence of a natural disaster is persistent (rational explanation)

Hypothesis 2b. The relative decrease in green bond yields after the occurrence of a natural disaster is temporary (behavioral explanation)

Another characteristic of natural disasters that is subject to conflicting predictions is novelty. The rational explanation remains neutral with respect to the role played by event novelty: the price responses of green and brown bonds keep reflecting their different levels of exposure to climate change risk without being influenced by the degree of novelty of the event. On the other hand, novelty increases the salience of an event. Events characterized by a higher degree of novelty are likely to trigger a stronger reaction among investors because new or unfamiliar events are more effective at capturing people's attention and trigger heightened emotional responses. At the same time, salience decreases as disasters become less unusual because repeated exposure to the same type of event over time diminishes investors' emotional response due to habituation. Thus, the behavioral explanation predicts that investors' overreaction is more pronounced after the occurrence of more unexpected disasters. We therefore formulate the following two conflicting hypotheses:

Hypothesis 3a. The relative decrease in green bond yields is not influenced by the degree of novelty of natural disasters (rational explanation)

Hypothesis 3b. The relative decrease in green bond yields is less pronounced after the occurrence of less unexpected natural disasters (behavioral explanation)

3. Sample, data and descriptive statistics

3.1 Bond data

We start by downloading the population of bonds issued worldwide from the beginning of 2015 to the end of 2021 from Refinitiv and apply the following filters: we exclude non-conventional securities such as certificates of deposit, commercial papers, and sukuks; we set a minimum issue amount of 100 million dollars; we exclude bonds with variable coupon. This first selection step leaves us with 150,894 bonds with a valid ISIN code. We then search for secondary market data on Refinitiv up to the end of 2022 and eliminate 68,488 bond issues with no such information. Also, we exclude 26,358 Eurobond issues, namely bonds issued offshore and denominated in a currency other than that of the issuer's country. Since we are interested into how investors react to natural disasters occurring where the bond is marketed, Eurobonds are not suitable for this purpose as they prevent from identifying a country of issue. Finally, since our analysis requires to observe the simultaneous price reaction of both brown and green bonds, we exclude 7,572 brown bonds whose trading period does not overlap with that of any green bond in the same country. We end up with a final sample of 48,476 bonds, resulting in 1,972,974 bond-month observations for the period 2015-2022.

Table 1 presents the sample. The number of bond-month observations is quite uniformly distributed across the sample years for brown bonds, while approximately half of the green bond observations are concentrated in the last two years, which reflects the recent growth of the green bond market. Overall, green bond observations account for 1.3% of our sample.

[Insert Table 1 here]

3.2 Natural disaster data

Our source of information on natural disasters is the EM-DAT database, maintained by the Centre for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain and used in prior research (e.g., Cavallo et al., 2013). It contains data on the occurrence and magnitude of worldwide natural disasters from 1900 to the present. Natural disasters can be categorized as biological (e.g., epidemic), climatological (e.g., drought), extra-terrestrial (e.g., collision), geophysical (e.g., earthquake), hydrological (e.g., flood), and meteorological (e.g., storm). Since our focus is on climate-related events that may alter investors' climate change risk perception, we confine our analysis to climatological, hydrological, and meteorological events.

We employ two disaster-related variables in our empirical analysis. A first, continuous variable is determined as the number of people affected by a disaster divided by the population of the country where the disaster occurs. This measure allows us to make use of all available information about the distribution of natural disasters and their severity over time and country. The database also provides information about the monetary amount of direct damage, which could serve as an alternative proxy for disaster severity. In line with Horvath (2021), we find the fraction of affected population preferable because monetary damages are determined based on information provided by insurance companies, which may be underestimated in developing countries due to low insurance coverage or overestimated by governments willing to attract more foreign aid.

A second, binary variable equals one in case a large-scale disaster occurs. As pointed out in prior studies, many of the events recorded in the EM-DAT database do not correspond to the common catastrophic notion of natural disaster as their impact is modest. We therefore follow Cavallo et al. (2013) and consider the 99^{th} percentile of the world distribution of the fraction of affected people (as defined above) as cutoff value to define a large-scale disaster. We end up with three large-scale disasters, a number that is broadly consistent with previous studies adopting a similar definition.[1]

[1] For instance, Cavallo et al. (2013) identify 8 large disasters during a 30-year period (1970-2000), whereas Horvath (2021) identifies 10 large disasters during the period 1960-2016.

These are: (1) a blizzard in January 2016 in the United States, also known as Snowzilla; (2) a flood in Japan in July 2018; (3) a flood in Belgium in July 2021.[2] Both the affected people and large-scale disaster variables are computed for each country-month of the sample.

Table 2 reports the year and type distributions of natural disasters. Panel A shows that the average disaster occurring in 2016 affects 1.217% of the population, which is the largest value over our sample period. As for large-scale disasters, we observe one event per year in 2016, 2018, and 2021. Panel B reports that approximately half of the disasters are meteorological (134 out of 278), of which 129 storms, followed by hydrological (96) and climatological (48) events. On average, storms are the most severe disasters with 0.219% of the population being affected.

[Insert Table 2 here]

3.3 Descriptive statistics

Table 3 reports some descriptive statistics about the brown and green bonds included in our sample.[3] The average yield to maturity of brown bonds is equal to 3.21% while that of green bonds is 2.37%, with the difference being statistically significant at the 1% level. This is broadly consistent with recent studies documenting a price premium or "greenium" for green bonds relative to their brown counterparts (e.g., Baker et al., 2022), although this univariate evidence does not control for heterogeneity between the two groups along other relevant characteristics. Green bonds are significantly smaller in terms of average issue size ($646.8 million vs. $1.6 billion), but the difference disappears between the median values ($500 vs. $477 million), which signals positive skewness in the issue size distribution of brown bonds. Also, while callable bonds are more frequently observed

[2] See, e.g.: en.wikipedia.org/wiki/January_2016_United_States_blizzard, en.wikipedia.org/wiki/2018_Japan_floods, and en.wikipedia.org/wiki/2021_European_floods#Belgium

[3] See Table A1 in Appendix A for variable definitions.

in the brown group (46.17% vs. 38.37%), senior bonds are more pervasive among green bonds (94.35% vs. 77.59%).

[Insert Table 3 here]

3.4 Methodology

We test our empirical predictions by means of two models. The first model is an OLS regression on the entire sample period as described in the following equations:

$$Yield_{i,t+1} = \alpha + \beta_1 Green_i \times Disaster_{i,t} + \beta_2 Disaster_{i,t} + \beta' Controls_i + Month_t + Issuer_i + Issue\_year_i + Currency_i + \varepsilon_{i,t} \quad (1)$$

$$Yield_{i,t+1} = \alpha + \beta_1 Green_i \times Disaster_{i,t} + Month_t + Bond_i + \varepsilon_{i,t} \quad (2)$$

where *i* denotes bond, and *t* denotes month. *Yield* is the annualized yield to maturity, *Green* is a dummy equal to one for green bonds, and *Disaster* takes the value of one of our two measures, namely *Affected people*, defined as the percentage of population affected by a disaster in the bond's country of issue (continuous), and *Large-scale disaster*, equal to one in case a large-scale disaster occurs in the bond's country of issue and zero otherwise (binary). β_1 is our coefficient of interest as it captures differences in the post-disaster behavior of green bond yields relative to brown bonds. In Equation (1), *Controls* represents a vector of the following bond-level characteristics, selected based on prior literature on bond pricing: *Ln(Issue amount)*, defined as the log of one plus the issue amount (in million dollars); *Ln(Maturity)*, defined as the log of one plus maturity (in years); the *Green, Putable*, *Callable*, *Guaranteed*, *Secured*, and *Senior* binary variables. We then include month fixed effects as well as issuer, issue year, and issue currency fixed effects. In Equation (2), month and bond fixed effects are included.[4]

The second model is a difference-in-differences (DD) regression that benchmarks green bonds' reaction to a large-scale disaster occurring in their country of issue against that of brown bonds traded over the same period and in the same country. Again, we adopt two model specifications, one with bond-level controls and one with bond fixed effects:

$$Yield_{i,t+1} = \alpha + \beta_1 Green_i \times Post_t + \beta' Controls_i + Month_t + Issuer_i + Issue\_year_i + Currency_i + \varepsilon_{i,t} \quad (3)$$

$$Yield_{i,t+1} = \alpha + \beta_1 Green_i \times Post_t + Month_t + Bond_i + \varepsilon_{i,t} \quad (4)$$

where *post* is a dummy variable that takes a value of one for post-disaster months, and zero otherwise. Again, β_1 is our coefficient of interest as it captures differences in the post-disaster yield of green bonds relative to brown bonds. Standard errors are always clustered by issuer.

4. Empirical results

4.1 Natural disasters and bond yields

In this section, we test our Hypothesis 1 that green bond yields decrease relative to brown bond yields after the occurrence of a natural disaster, and investigate whether the magnitude of this effect increases with disaster severity. Table 4 reports the results. Panel A shows the estimates of the baseline regression on the percentage yield to maturity. The *Disaster* variable corresponds to the percentage of affected people in Models 1 and 2 and to the large-scale disaster dummy in Models 3 and 4.

[4] We do not include credit rating among the independent variables because we always control for issuer or bond fixed effects. See Table A1 in Appendix A for variable definitions.

We find a negative and statistically significant (at the 1% level) coefficient of the *Green* × *Disaster* variable in all models. This documents that green bond yields exhibit a decrease relative to those of brown bonds after a natural disaster. In terms of economic impact, the magnitude of the coefficients in Models 1 and 2 implies a 2.6-2.7 basis points decrease for a one percentage point increase in the affected population. In Models 3 and 4, the coefficients of the *Green* × *Disaster* variable indicate a 60-63 basis points drop in green bond yields relative to brown bond yields after the occurrence of a large-scale disaster. This evidence is new to the literature and provides empirical support to Hypothesis 1 that green bond yields decrease relative to brown bond yields after the occurrence of a natural disaster, and the magnitude of this effect increases with disaster severity. Also, the positive and significant coefficient of the *Disaster* variable across all models indicates that natural disasters depress brown bond prices, while the negative and significant coefficient of the *Green* dummy documents the presence of a 6.8-6.9 basis points "greenium" that persists in a multivariate setting.

Panel B reports the estimates of the DD regressions on the [-3,+3] and [-6,+6] month intervals centered around the occurrence of a large-scale disaster. The coefficient of the *Green* × *Post* variable is negative and statistically significant at the 1% level across all models. Consistent with the evidence in Panel A, this documents that green bond yields decrease relative to brown bond yields after a natural disaster. The magnitude of the coefficient implies an average 34 (31) basis points decrease over a [-3,+3] ([-6,+6]) month window. Figure 1 offers a clear picture of the green and brown bond yield patterns around large-scale disasters. While the green bond series (continuous line) exhibits a decrease in the post-disaster period, the brown bond series (dashed line) experiences an increase which partly reverts over time. This evidence provides further support to Hypothesis 1.

[Insert Table 4 here]

[Insert Figure 1 here]

4.2 The demand channel

We now investigate whether the relative decrease in green bond yields can be explained by a stronger demand experienced by green bonds relative to that of brown bonds in the immediate aftermath of a disaster. We do so by analyzing liquidity patterns of green and brown bonds as proxied for by the bid-ask spread, defined as the difference between the end-of-month closing ask and bid prices divided by their midpoint.[5] We replicate our baseline regressions with bid-ask spread as dependent variable and both our disaster-related measures, namely *Affected people* and *Large-scale disaster*, as explanatory variables.

The evidence is reported in Table 5. The coefficient of the *Green* × *Disaster* variable is negative and significant at the 1% level in all model specifications. In Models 1 and 2, the magnitude of the coefficients imply an average 0.2-0.3 basis points decrease in green bond bid-ask spread, relative to that of brown bonds, for each percentage point increase in a country's population affected by a disaster. In Models 3 and 4, the coefficients indicate a 4.4-8.0 basis points relative narrowing in the bid-ask spread of green bonds following a large-scale disaster. Thus, the liquidity pattern of green bonds diverges from that of brown bonds and once again this divergence becomes more pronounced after more severe disasters. This is consistent with a relatively stronger demand experienced by green bonds and explains the previously documented divergence in the price reaction of green and brown bonds.

[Insert Table 5 here]

[5] We considered turnover as an alternative liquidity proxy, but data are available for a too limited amount of observations.

4.3 Issuer's environmental score

A cross-sectional implication arising from the above evidence on the effect of natural disasters on green bond yields is that, if some green bonds were perceived to be safer than others, then they should be particularly sought after following a natural disaster. Instead of treating green bonds as a homogeneous category, we explore a possibly varying price impact of natural disasters within green securities. We do so by exploiting cross-sectional differences that allow us to identify bonds that are "greener" than others, one of which is the degree of sustainability of the bond issuer. We then expect the relative decrease in green bond yields to be more pronounced for bonds issued by entities with a better environmental score.

After retrieving environmental scores from Refinitiv, we estimate our baseline regression models by adding a triple interaction term, namely *Green* × *Disaster* × *E score*, which is aimed at capturing whether the relative decrease in green bond yields varies with the issuer's environmental score. Table 6 reports the results. The coefficients of the triple interaction term are always negative and significant at the 1% level, which confirms our prediction that the relative decrease in green bond yields in the aftermath of a disaster is larger for issuers with a better environmental score. This evidence holds for both disaster measures, namely the percentage of a country's population affected by a disaster (Models 1-2) and the occurrence of a large-scale disaster (Models 3-4). Also, it is interesting to note that the coefficient of the *Disaster* × *E score* variable is negative and significant across all models, which indicates that the average price impact of a natural disaster is attenuated when bonds are issued by entities with a high environmental score. Overall, these results corroborate our findings that investors move to green assets as a response to adverse climate shocks, especially to those green assets that are perceived to be better hedged against climate change risk.

[Insert Table 6 here]

5. Rational vs. behavioral explanation

In this section, we investigate whether the evidence of a decrease in green bond yields relative to brown bonds is due to a rational or a behavioral mechanism, or a combination of the two. We do so by focusing on two attributes on which these explanations generate conflicting predictions, namely the persistence of the disaster-induced effect on bond prices and the role played by disaster novelty.

5.1 Persistence of the effect of natural disasters on bond yield

The rational explanation predicts that the price impact of natural disasters on bond prices is persistent as long as they convey new information about increasing climate change risk (Hypothesis 2a). The behavioral explanation, on the other hand, implies that investors overreact in the immediate aftermath of a disaster, but their overreaction fades with time as the disaster becomes less salient (Hypothesis 2b). To disentangle their roles, we estimate a DD model around large-scale disasters where we quantify the variation in green bond yields for each post-disaster month. The idea is to analyze whether and when the relative decrease in green bond yields disappears sometime after the disaster.

Table 7 presents the results. *Month t+X* is the coefficient of the interaction term between the *Green* dummy and the *PostX* binary variable which equals one only in month *t+X*, where *t* is the disaster month and *X* is an integer that takes values from one to six. In line with the previous analyses, we estimate a specification with bond-level controls (Model 1) and another with bond fixed effects (Model 2). The coefficients in Model 1 show that the average difference between green and brown bond yields amounts to -60.2, -46.8, and -33.8 basis points in the first, second, and third post-disaster month, respectively. The absolute value of the three coefficients decreases over time, indicating a considerable attenuation of the effect, which is consistent with a behavioral component that grows weaker as the salience of the event decreases. Six months later, the average difference is still significant at the 5% level and equal to 13.3 basis points, a 78% reduction in magnitude from the first month after the disaster. The evidence in Model 2 documents the same pattern. This indicates that the disaster-induced decrease in green bond yields relative to brown bonds has both a temporary and a persistent component, and the temporary component accounts for the majority of the immediate reaction. In other words, the evidence documents that the price impact of natural disasters cannot be exclusively traced back to one or the other explanation, but to a combination of the two. Investors overreact in the immediate aftermath of a disaster, when event salience peaks, but the effect subsides with time, consistent with a behavioral effect (Hypothesis 2b). Still, the variation does not fully reabsorbs, consistent with the presence of a rational mechanism (Hypothesis 2a).

[Insert Table 7 here]

5.2 Disaster repetitiveness and the effect on bond yield

Another important aspect that is subject to conflicting predictions is disaster novelty. While the rational explanation does not provide any theoretical argument based on which the price impact of natural disasters should be sensitive to their degree of novelty (Hypothesis 3a), the behavioral explanation implies that less unexpected events are less salient and therefore generate a weaker reaction (Hypothesis 3b). We therefore examine whether the post-disaster decrease in green bond yields relative to brown bonds alleviates when disasters become more repetitive. We do so by estimating our baseline regression model with the addition of a country-level count variable (*Count*) which equals one for all countries in the first month of our sample period and increases by one if a disaster occurs in a given country-month (if no disasters occur, *Count* remains constant). The triple interaction *Green* × *Disaster* × *Count* is therefore aimed at capturing whether the effect on bond yields varies with disaster repetitiveness.

Results are reported in Table 8. In Models 1 and 2, where the *Disaster* variable corresponds to the percentage of affected people, the coefficient of the triple interaction term is positive and significant at the 5% and 10% levels, respectively. Together with the negative and significant coefficient of the *Green* × *Disaster* variable, the evidence indicates that the disaster-induced decrease in green bond yields relative to brown bonds becomes less pronounced as disasters become more repetitive. In economic terms, the price impact of a large-scale disaster weakens by an average 2.4-3.2 basis points for each subsequent disaster occurrence. Similarly, in Models 3 and 4, we find that the coefficients of the triple interaction term are both positive at the 5% significance level, suggesting that the price effect grows weaker as large-scale disasters become less unusual. Overall, the evidence is consistent with the presence of a behavioral component in green bonds' price reaction to natural disasters, consistent with Hypothesis 3b.

[Insert Table 8 here]

6. Additional analyses and robustness tests

In this section, we perform a number of additional tests to check the robustness of our empirical evidence to possible alternative explanations.

6.1 The behavior of bonds in unaffected countries

A possible concern arising from our analyses is that the variation in green bond yields is due to an unobserved shock that happens to be contemporary and unrelated with the disaster and affects the bond markets of multiple countries (e.g., a regulatory intervention at a regional level focusing on green bonds). To assess the plausibility of this alternative explanation, we test whether our evidence persists after benchmarking the post-disaster reaction of green bonds not only against that of brown bonds traded in the same country, but also against that of bonds traded in countries that are unaffected by the disaster. We do so by estimating a triple differences model that accounts for a third difference in addition to the two differences that we already exploit in our empirical analysis (the reaction of green bond yield to a natural disaster and the reaction of green versus brown bonds), namely the reaction of bonds issued in the country where the disaster occurs versus the contemporaneous reaction of bonds issued in unaffected countries. Consistently, we add the *Treat* variable which equals one for countries affected by a disaster and zero otherwise. *Green* and *Post* equal one for green bonds and post-disaster months, respectively. Table 9 reports the results. The coefficients of the *Green* × *Disaster* × *Treat* variable are negative and significant at the 1% level across all time windows and model specifications. This confirms our evidence and indicates that green bond yields, net of variation in brown bond yields, from before to after a disaster respond more negatively in countries where the disaster occurs relative to unaffected countries. Overall, the evidence of a relative decrease in green bond yields induced by natural disasters persists after using bonds traded in unaffected countries as a further control sample.

[Insert Table 9 here]

6.2 Dual issuers

Another possible alternative explanation to our evidence is that the relative decrease in green bond yields is driven by the fact that issuers who are committed to green projects (as indicated by their decision to issue a green bond) are perceived as being less risky relative to brown bond issuers after the occurrence of a natural disaster. According to this view, a natural disaster would trigger a shift in investors' perception of green bond issuers rather than green bonds. If this was the case, then we should observe a decrease in the yield of all debt of green bond issuers, with no difference between green and brown securities. We address this concern by estimating our baseline regression models on the subsample of dual issuers, namely issuers of both green and brown bonds. To control for possible variations in investors' risk perception of green bond issuers over time, we add *Issuer* × *Month* fixed effects. Results are reported in Table 10. The coefficient of the *Green* × *Disaster* interaction term remains negative and statistically significant across all model specifications, although at a lower significance level than in our previous analyses (5% instead of 1%). The evidence confirms that green and brown bonds react differently to natural disasters even if they are issued by the same entity, which makes the above alternative explanation unlikely to drive our results.

[Insert Table 10 here]

6.3 Foreign bonds

Our empirical analysis focuses on the price reaction of bonds traded in the country where the disaster occurs, which does not always correspond to the country where the bond issuer is domiciled. More specifically, 10,270 out of 48,476 bonds (21.2%) are issued abroad. Since the majority of our sample bonds is marketed in the country where the issuer is physically located, this raises the concern that the price impact could be simply due to the economic damages caused by the materialization of physical climate risk to the issuer. We note that this explanation fails to justify why green and brown bonds issued by the same entity react differently to a natural disaster, given that the damage caused to the issuer's assets should uniformly affect all its debt securities. Still, we empirically address this concern by estimating our model on the subsample of foreign bonds, namely bonds issued in a country that is different from that of the issuer's domicile. If the price reaction were exclusively driven by physical damage suffered from the issuer's assets, then we should observe no effect of natural disasters occurring in countries where foreign bonds are traded. However, results in Table 11 show that the evidence persists.

[Insert Table 11 here]

7. Conclusions

This study shows how green and brown bond prices react to materializations of climate change risk. We find that green bonds experience a decrease in yields relative to brown bonds in the immediate aftermath of a natural disaster, with this effect growing larger after more severe disasters. Since green assets are better hedged against climate change risk than brown assets, the occurrence of a natural disaster strengthens investors' preference for green bonds, which in turn experience an increase in demand in the immediate aftermath. Our analysis of green and brown bond liquidity patterns is consistent with this view.

We then go on to investigate whether this price reaction is due to a rational or a behavioral mechanism. We find evidence consistent with a combination of the two. While the widening in the brown-green yield spread does not revert to pre-disaster levels, a significant fraction of it disappears a few months after the disaster, suggesting the presence of both a temporary and a persistent component. Also, the price impact grows weaker when disasters become more repetitive, consistent with the presence of a behavioral effect. Overall, while the different reaction of green and brown bonds to natural disasters is consistent with their different exposure to climate change risk, part of this evidence is driven by investor overreaction in the immediate aftermath of a disaster. While most of the evidence is based on equity securities and models climate change as a systematic risk source, we add to the debate on the pricing difference between green and brown securities in the bond market by documenting their different responses to extreme climate-related events. Specifically, we shed light on how rational and behavioral mechanisms coexist and determine such response.

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Table 1. Sample distribution. Year distribution of the bond-month observations of the sample of 48,476 bonds traded worldwide from Jan 1, 2015 to Dec 31, 2022.

	Brown bonds		Green bonds		Total	
	No.	%	No.	%	No.	%
2015	165,537	8.5	481	1.8	166,018	8.4
2016	191,741	9.8	974	3.7	192,715	9.8
2017	208,497	10.7	1,456	5.5	209,953	10.6
2018	243,727	12.5	2,093	7.9	245,820	12.5
2019	260,566	13.4	2,978	11.3	263,544	13.4
2020	277,050	14.2	4,276	16.2	281,326	14.3
2021	299,233	15.4	6,138	23.3	305,371	15.5
2022	300,266	15.4	7,961	30.2	308,227	15.6
Total	1,946,617	98.7	26,357	1.3	1,972,974	100.0

Table 2. Natural disasters. Year (Panel A) and type (Panel B) distribution of natural disasters during the period 2015-2022. Only disasters occurring in country-months where both green and brown bonds are traded are included. Affected people is the average percentage of a country's population affected by a disaster. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period.

Panel A. Year	Disasters (no.)	Affected people (% pop., average)	Large-scale disasters (no.)
2015	27	0.004	0
2016	22	1.217	1
2017	29	0.025	0
2018	26	0.071	1
2019	34	0.017	0
2020	27	0.019	0
2021	67	0.020	1
2022	46	0.036	0
Panel B. Disaster type			
Climatological	48	0.025	0
Wildfire	48	0.025	0
Hydrological	96	0.041	2
Flood	90	0.044	2
Landslide	6	0.004	0
Meteorological	134	0.212	1
Extreme temperature	5	0.020	0
Storm	129	0.219	1
Total	278	0.207	3

Table 3. Descriptive statistics. Sample of 48,476 bonds traded worldwide from Jan 1, 2015 to Dec 31, 2022. Yield is the percentage annualized yield to maturity (frequency is monthly). All other variables are bond-specific. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively, of the t-test (mean) and Wilcoxon signed-rank test (median) of the difference between the two groups (a test of proportions is used for binary variables).

	Brown bonds			Green bonds			Difference brown - green	
	Mean	Median	N	Mean	Median	N		
Yield (%)	3.21	2.55	1,946,617	2.37	1.97	26,357	0.84***	0.59***
Issue amount ($m)	1,591.5	477.0	47,715	646.8	500.0	761	1,002.3***	-23.0
Maturity (years)	9.07	7.01	47,715	9.46	7.50	761	-0.39	-0.49*
Putable (% bonds)	0.11	-	47,715	0.00	-	761	0.11	-
Callable (% bonds)	46.17	-	47,715	38.37	-	761	7.80***	-
Guaranteed (% bonds)	22.16	-	47,715	19.45	-	761	2.71*	-
Secured (% bonds)	13.38	-	47,715	14.98	-	761	-1.60	-
Senior (% bonds)	77.59	-	47,715	94.35	-	761	-16.76***	-

Table 4. Natural disasters and bond yield. The dependent variable is the percentage annualized yield to maturity. Panel A is a regression on the entire sample. In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month. Disaster variables are lagged one month. Panel B is a difference-in-differences regression around large-scale disasters. Models 1 and 2 (3 and 4) are estimated over the [-3,+3] ([-6,+6]) month interval, with month zero being the month of occurrence of a large-scale disaster. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Green equals one for green bonds. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

Panel A. Regression on the entire sample				
	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster	-0.0256***	-0.0267***	-0.6038***	-0.6280***
	[0.0063]	[0.0056]	[0.1539]	[0.1358]
Disaster	0.0245***	0.0270***	0.4085***	0.4617***
	[0.0038]	[0.0031]	[0.0920]	[0.0822]
Green	-0.0685***		-0.0684***	
	[0.0224]		[0.0224]	
Ln(Issue amount)	-0.0387*		-0.0389**	
	[0.0198]		[0.0198]	
Ln(Maturity)	1.0421***		1.0421***	
	[0.0261]		[0.0261]	
Putable	-1.8117***		-1.8117***	
	[0.5841]		[0.5841]	
Callable	0.1655***		0.1650***	
	[0.0269]		[0.0270]	
Guaranteed	-0.0325		-0.0325	
	[0.0625]		[0.0625]	
Secured	-0.7078***		-0.7080***	
	[0.0944]		[0.0944]	
Senior	-0.1694***		-0.1685***	
	[0.0442]		[0.0442]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.7896	0.8305	0.7896	0.8305
Observations	1,972,974	1,972,974	1,972,974	1,972,974

Panel B. DD around large-scale disasters				
	[-3, +3]		[-6, +6]	
	(1)	(2)	(3)	(4)
Green x Post	-0.3416***	-0.3372***	-0.3085***	-0.3076***
	[0.0760]	[0.0761]	[0.0744]	[0.0758]
Green	0.0915		0.0989	
	[0.0792]		[0.0820]	
Ln(Issue amount)	-0.0610**		-0.0628**	
	[0.0310]		[0.0282]	
Ln(Maturity)	1.5421***		1.5552***	
	[0.0578]		[0.0564]	
Putable	0.5317***		0.5271***	
	[0.1772]		[0.1683]	
Callable	0.1897***		0.1902***	
	[0.0379]		[0.0355]	
Guaranteed	0.1041		0.1370	
	[0.1377]		[0.1377]	
Secured	-1.0716***		-1.1182***	
	[0.3395]		[0.3382]	
Senior	-0.3808***		-0.3773***	
	[0.1234]		[0.1188]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.9412	0.9563	0.9201	0.9352
Observations	86,910	86,910	156,919	156,919

Table 5. Effect of natural disasters on bond liquidity. The dependent variable is the percentage bid-ask spread, computed as the difference between the closing ask and bid prices divided by their midpoint. Green equals one for green bonds. In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month (country is the bond's country of issue). Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Disaster variables are lagged one month. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster	-0.0032***	-0.0022***	-0.0796***	-0.0442***
	[0.0009]	[0.0004]	[0.0245]	[0.0114]
Disaster	0.0029***	0.0015***	0.0514***	0.0121
	[0.0005]	[0.0004]	[0.0119]	[0.0105]
Green	-0.0085		-0.0085	
	[0.0113]		[0.0113]	
Ln(Issue amount)	-0.0363***		-0.0363***	
	[0.0073]		[0.0073]	
Ln(Maturity)	0.3669***		0.3669***	
	[0.0187]		[0.0187]	
Putable	-0.0797		-0.0797	
	[0.1136]		[0.1136]	
Callable	-0.0271**		-0.0272**	
	[0.0118]		[0.0118]	
Guaranteed	0.0023		0.0023	
	[0.0142]		[0.0142]	
Secured	-0.1369***		-0.1369***	
	[0.0187]		[0.0187]	
Senior	-0.0825***		-0.0824***	
	[0.0178]		[0.0178]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.6031	0.7526	0.6031	0.7526
Observations	1,972,974	1,972,974	1,972,974	1,972,974

Table 6. Natural disasters and bond yield: issuer's environmental score. The dependent variable is the percentage annualized yield to maturity. Green equals one for green bonds. In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month (country is the bond's country of issue). E score is the issuer's environmental score. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Disaster variables are lagged one month. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster x E score	-0.0029***	-0.0021***	-0.0691***	-0.0528***
	[0.0008]	[0.0007]	[0.0228]	[0.0185]
Green x Disaster	0.2393***	0.1717***	5.6052***	4.2985***
	[0.0692]	[0.0591]	[2.0311]	[1.6534]
Disaster x E score	-0.0004***	-0.0003***	-0.0113***	-0.0087***
	[0.0001]	[0.0001]	[0.0034]	[0.0030]
Green x E score	0.0021	0.0069	0.0021	0.0069
	[0.0036]	[0.0055]	[0.0036]	[0.0055]
E score	0.0006	0.0015	0.0006	0.0015
	[0.0016]	[0.0017]	[0.0016]	[0.0017]
Disaster	0.0494***	0.0410***	1.0900***	0.8870***
	[0.0084]	[0.0072]	[0.2202]	[0.1913]
Green	-0.1976		-0.1967	
	[0.2924]		[0.2921]	
Ln(Issue amount)	-0.0398		-0.0399	
	[0.0306]		[0.0306]	
Ln(Maturity)	1.2640***		1.2640***	
	[0.0196]		[0.0196]	
Putable	0.8398**		0.8402**	
	[0.3799]		[0.3800]	
Callable	0.0623**		0.0621**	
	[0.0298]		[0.0298]	
Guaranteed	0.2422**		0.2422**	
	[0.0978]		[0.0978]	
Secured	-1.0795***		-1.0798***	
	[0.2042]		[0.2042]	
Senior	-0.2803***		-0.2797***	
	[0.0476]		[0.0476]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.7561	0.8141	0.7561	0.8141
Observations	518,869	518,869	518,869	518,869

Table 7. Persistence of the effect of natural disasters on bond yield. Difference-in-differences regression around large-scale disasters estimated over the [-6,+6] month interval, with month zero being the month of occurrence of a large-scale disaster. The dependent variable is the percentage annualized yield to maturity. Coefficients of the Month t+X variables refer to the Green x Post interaction term. Green equals one for green bonds. Post equals one in month t+X, with t being the month of occurrence of a large-scale disaster, and zero otherwise. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Controls include Ln(Issue amount), Maturity, Putable, Callable, Guaranteed, Secured, Senior. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	(1)	(2)
Month t+1	-0.6019***	-0.6024***
	[0.1027]	[0.1033]
Month t+2	-0.4675***	-0.4669***
	[0.1244]	[0.1263]
Month t+3	-0.3376***	-0.3351***
	[0.0874]	[0.0884]
Month t+4	-0.1440**	-0.1404**
	[0.0666]	[0.0684]
Month t+5	-0.1595***	-0.1586***
	[0.0581]	[0.0587]
Month t+6	-0.1328**	-0.1318**
	[0.0662]	[0.0658]
Controls	Yes	No
Bond FE	No	Yes
Month FE	Yes	Yes
Issuer FE	Yes	No
Bond issue year FE	Yes	No
Bond currency FE	Yes	No
Adjusted R-squared	0.9201	0.9352
Observations	156,919	156,919

Table 8. Bond yield and disaster repetitiveness. The dependent variable is the percentage annualized yield to maturity. Green equals one for green bonds. Count is a country-level variable that equals one for the first month of the sample period and increases by one in months when a disaster occurs (in months with no disasters, the variable remains constant). In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month (country is the bond's country of issue). Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Disaster variables are lagged one month. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster x Count	0.0324**	0.0242*	0.0664**	0.0775**
	[0.0163]	[0.0134]	[0.0328]	[0.0374]
Green x Disaster	-0.4115**	-0.3156*	-1.5408***	-1.6424***
	[0.1971]	[0.1636]	[0.3862]	[0.4283]
Green x Count	-0.0022*	-0.0045	-0.0049***	-0.0035
	[0.0012]	[0.0049]	[0.0012]	[0.0064]
Disaster x Count	0.0256***	0.0182***	-0.1154***	-0.1152***
	[0.0042]	[0.0032]	[0.0278]	[0.0295]
Disaster	-0.2827***	-0.1934***	1.8918***	1.9348***
	[0.0529]	[0.0401]	[0.3480]	[0.3663]
Count	0.0059***	0.0039**	0.0035***	0.0050***
	[0.0012]	[0.0017]	[0.0012]	[0.0017]
Green	0.0089		0.0776**	
	[0.0442]		[0.0394]	
Ln(Issue amount)	0.0234		-0.0411**	
	[0.0177]		[0.0196]	
Ln(Maturity)	0.3787***		1.0436***	
	[0.0465]		[0.0261]	
Putable	-1.6765***		-1.8175***	
	[0.5679]		[0.5837]	
Callable	0.2033***		0.1584***	
	[0.0370]		[0.0271]	
Guaranteed	-0.0347		-0.0316	
	[0.0543]		[0.0625]	
Secured	-0.4662***		-0.7107***	
	[0.0799]		[0.0943]	
Senior	-0.0144		-0.1658***	
	[0.0481]		[0.0446]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.7824	0.823	0.7896	0.8304
Observations	1,972,974	1,972,974	1,972,974	1,972,974

Table 9. Triple difference regression around large-scale disasters. The dependent variable is the percentage annualized yield to maturity. Models 1 and 2 (3 and 4) are estimated over the [-3,+3] ([-6,+6]) month interval, with month zero being the month of occurrence of a large-scale disaster. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Green equals one for green bonds. Post equals one for post-disaster months. Treat equals one for disaster countries. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	[-3, +3]		[-6, +6]	
	(1)	(2)	(3)	(4)
Green x Post x Treat	-0.1230***	-0.1081***	-0.1377***	-0.1125***
	[0.0219]	[0.0219]	[0.0327]	[0.0333]
Post x Treat	0.1179***	0.1168***	0.1848***	0.1849***
	[0.0118]	[0.0119]	[0.0143]	[0.0146]
Green x Post	0.0352**	0.0277*	0.0717***	0.0591***
	[0.0145]	[0.0144]	[0.0211]	[0.0209]
Green x Treat	-0.1538***		-0.1358***	
	[0.0498]		[0.0504]	
Green	0.0843***		0.0496	
	[0.0306]		[0.0309]	
Treat	-0.0140		-0.0328	
	[0.0879]		[0.0863]	
Ln(Issue amount)	-0.0415*		-0.0420**	
	[0.0220]		[0.0213]	
Ln(Maturity)	1.2320***		1.2098***	
	[0.0280]		[0.0275]	
Putable	-1.1768***		-1.1505***	
	[0.4269]		[0.4460]	
Callable	0.0559**		0.0699***	
	[0.0274]		[0.0264]	
Guaranteed	0.0085		0.0024	
	[0.0707]		[0.0677]	
Secured	-0.7873***		-0.7571***	
	[0.1098]		[0.1060]	
Senior	-0.1042**		-0.1057**	
	[0.0471]		[0.0466]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.8507	0.8978	0.8449	0.8901
Observations	428,628	428,628	776,366	776,366

Table 10. Effect of natural disasters on dual issuers' bond yield. The sample is restricted to dual issuers, namely issuers of both green and brown bonds. The dependent variable is the percentage annualized yield to maturity. Green equals one for green bonds. In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month (country is the bond's country of issue). Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Disaster variables are lagged one month. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster	-0.0065**	-0.0045**	-0.1528**	-0.0929**
	[0.0030]	[0.0018]	[0.0709]	[0.0460]
Disaster	-0.0185***	-0.0066***	-0.5920***	-0.3025***
	[0.0024]	[0.0017]	[0.0518]	[0.0438]
Green	0.0852***		0.0852***	
	[0.0189]		[0.0189]	
Ln(Issue amount)	-0.0441*		-0.0440*	
	[0.0238]		[0.0238]	
Ln(Maturity)	0.8902***		0.8902***	
	[0.0306]		[0.0306]	
Putable	-0.2665***		-0.2664***	
	[0.0726]		[0.0726]	
Callable	0.3160***		0.3160***	
	[0.0254]		[0.0254]	
Guaranteed	0.0628		0.0627	
	[0.0720]		[0.0720]	
Secured	-0.5110***		-0.5111***	
	[0.1030]		[0.1030]	
Senior	-0.3459***		-0.3461***	
	[0.0895]		[0.0895]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Issuer x Month FE	Yes	Yes	Yes	Yes
Adjusted R-squared	0.8274	0.9091	0.8274	0.9091
Observations	472,721	472,721	472,721	472,721

Table 11. Foreign bonds. The sample is restricted to foreign bonds, namely bonds issued in a country that differs from the issuer's country of domicile. The dependent variable is the percentage annualized yield to maturity. In Models 1 and 2, the disaster variable is the percentage of population affected by a natural disaster in each country-month. In Models 3 and 4, the disaster variable equals one if a large-scale disaster occurs in a given country-month. Disaster variables are lagged one month. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period. Green equals one for green bonds. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Issuer-clustered standard errors are reported in brackets.

	Affected people		Large-scale disaster	
	(1)	(2)	(3)	(4)
Green x Disaster	-0.0283***	-0.0346***	-0.7593***	-0.9074***
	[0.0072]	[0.0074]	[0.1891]	[0.1956]
Disaster	0.0234***	0.0282***	0.5391***	0.6467***
	[0.0040]	[0.0036]	[0.0962]	[0.0871]
Green	-0.0635		-0.0637	
	[0.0503]		[0.0502]	
Ln(Issue amount)	0.1240*		0.1239*	
	[0.0729]		[0.0729]	
Ln(Maturity)	1.1240***		1.1240***	
	[0.0582]		[0.0582]	
Putable	-1.2229		-1.2229	
	[2.1124]		[2.1123]	
Callable	0.0914		0.0912	
	[0.0947]		[0.0947]	
Guaranteed	-0.1851		-0.1850	
	[0.1471]		[0.1471]	
Secured	-0.8845***		-0.8846***	
	[0.2466]		[0.2466]	
Senior	-0.0316		-0.0316	
	[0.0722]		[0.0722]	
Bond FE	No	Yes	No	Yes
Month FE	Yes	Yes	Yes	Yes
Issuer FE	Yes	No	Yes	No
Bond issue year FE	Yes	No	Yes	No
Bond currency FE	Yes	No	Yes	No
Adjusted R-squared	0.7599	0.8041	0.7599	0.8041
Observations	464,965	464,965	464,965	464,965

Figure 1. Bond yield around large scale disasters. The graph shows the average green and brown bond yield over the [-6,+6] month window around large-scale disasters. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period.

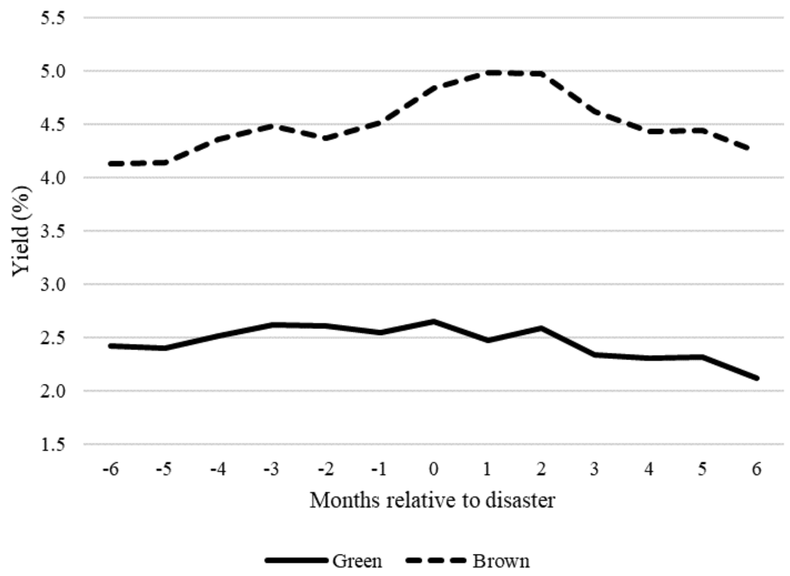

Table A1. Variable definitions

Name	Definition	Data source
Bid-Ask spread	Difference between the closing ask and bid prices divided by their midpoint	Refinitiv
Callable	Binary variable equal to one if the bond contains an embedded call option	Refinitiv
Disaster (affected people)	Number of people affected by natural disasters in each country-month divided by the country's population measured at the beginning of the year, expressed in percentage	EM-DAT
Disaster (large-scale)	Binary variable equal to one if a large-scale disaster occurs in a given country-month. Large-scale disasters are in the top 1% of the disaster distribution by percentage of affected population over the sample period.	EM-DAT
E score	Environmental score of the bond issuer	Refinitiv
Green	Binary variable equal to one if the bond was issued as a self-labeled green bond	Refinitiv
Guaranteed	Binary variable equal to one if the bond is backed by a third-party guarantee	Refinitiv
Issue amount	Amount of capital raised through bond issuance	Refinitiv
Maturity	Maturity period	Refinitiv
Putable	Binary variable equal to one if the bond contains an embedded put option	Refinitiv
Secured	Binary variable equal to one if the bond is secured by an asset which serves as collateral	Refinitiv
Senior	Binary variable equal to one for senior bonds	Refinitiv
Yield	Annualized yield to maturity	Refinitiv