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The changing value of the 'green' label on the US municipal bond market

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Green bonds are seen as a key instrument to unlock climate finance. While their volume has grown steadily in recent years, the impact of the 'green' label on the bond market is poorly understood. Here, we investigate the differences between the yield term structures of green and conventional bonds in the US municipal bond market. We show that, although returns on conventional bonds are on average higher than for green bonds, the differences can largely be explained by the fundamental properties of the bonds. Historically, green bonds have been penalized on the municipal market, being traded at lower prices and higher yields than expected by their credit profiles. In recent years, however, the credit quality of municipal green bonds has increased and the premium turned positive. Green bonds are thus becoming an increasingly attractive investment, with scope to bridge the climate finance gap for mitigation and adaptation.

The large gap between needed and supplied finance for mitigation and adaptation projects has been identified as an important challenge for climate action[1]. On the one hand, actors in the field put forward the lack of adequate funding as one of the key barriers to the implementation of climate mitigation projects[2,3]. On the other hand, financial institutions emphasize the lack of an appropriate framework for green-oriented investments despite the existence of a potentially large demand[4]. Against this background, the rise of green bonds, whose volume has grown to US$300 billion since 2008, is emphasized as a major success and appears as one of the key instruments to bridge the climate finance gap.

As far as their financial structure is concerned, green bonds are identical to conventional bonds. They are tradable fixed-income securities under which the issuer owes the holders a debt and, conditional on the terms under which the bond was issued, is required to pay them interest (the coupon) and/or to redeem the principal at a later date, denoted the maturity date. They are labelled as green because the issuer pledges to use the proceeds of the bonds for environmental or climate-focused activities in accordance with sustainable development standards, such as the Green Bond Principles released by the International Capital Market Association[5]. Most green bonds are firstly self-labelled by the issuer but an increasing share of the issuances (80% as of 2016 according to)[6] is also reviewed by third parties[7]. These provide second opinions on the green nature of a bond that investors can use to determine whether green bonds meet their expectations. Similarly, some financial data providers maintain databases of green bonds for which they have checked that the planned use of proceeds is consistent with the Green Bond Principles[8]. Our analysis relies in this respect on the database established by Bloomberg[9].

Green bonds have been issued by a wide range of entities: corporations, governments on a local (municipal) and national level, and international organizations. Their volume is relatively large: US$70 billion were issued in 2016 and US$50 to US$100 billion in additional emission volume is expected for 2017 (see the Resource Center of the World Bank[10] for complementary statistics and insights). Hence, they have become a mainstream financial instrument. With their financial properties being identical, green bonds should thus, in theory, attract the same demand as conventional bonds from investors, for which environmental questions are not the determining factor. In addition, they should attract further demand from investors concerned with environmental sustainability. As a whole, a green bond shall be more highly demanded than its conventional counterpart. Therefore, it shall trade at a higher price and yield a lower interest rate. Hence, environmentally sustainable projects shall benefit from better financing conditions and pass the profitability threshold more easily. In turn, entrepreneurs should be attracted, and growth stimulated in the corresponding sectors. From a systemic perspective, green bonds shall provide means for individuals to influence the direction of economic growth through the allocation of their savings.

Here, we provide an empirical analysis of these assumptions. Although two bonds, even from the same issuer, are never perfectly comparable as they might differ in some quantitative and qualitative dimensions, we use issuance and transaction data from a large and well-structured bond market, the US municipal bond market, to compare the yield of green and conventional bonds with similar characteristics. By comparing their yield curves, we find that green bonds on average pay a lower interest rate and hence provide better financing conditions than conventional bonds. However, a quantitative analysis based on the Oaxaca–Blinder decomposition[11,12] shows that this spread can be mainly explained by the characteristics of the issuing entity, irrespectively of the green nature of the bond. Moreover, the characteristics of green bonds on the US municipal market seem to have been amplified by the market, giving rise to a 'reputational' green premium. This premium has been negative in the first five years of the market, in which green bonds had on average a comparatively lower credit quality. In the last two years of our observations, this premium turned positive as the relative credit quality of green bonds has improved. Hence, although green bonds currently benefit from a positive premium, it is unclear whether this is due to herding behaviour and reputation externalities, or if there indeed exists a large enough specific demand for green bonds. Concurrent research shows similar results partly also hold for the corporate bonds market[13].

Results

Yield term structures. A comparative analysis of green and conventional bonds implies two important caveats. First, green bonds

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cannot be unambiguously identified. Second, the green bond market, with approximately US$250 billion outstanding, is tiny with regards to the US$100 trillion of the conventional bond market. Our approach to the issue of identification of green bonds is to use the database constructed by Bloomberg[9], which tags bonds as green if the proceeds are to be used consistently with the Green Bond Principles; that is, 'towards projects or activities that promote climate change mitigation or adaptation or other environmental sustainability purposes'[5] (see the Bloomberg Green Bond Database section in the Methods). Concerning the issue of the difference in size between the conventional and green bond market, we focus on the municipal bond market, which forms the largest category within the Bloomberg Green Bond Database, to obtain samples of green and conventional bonds of the same set of issuers that can be meaningfully compared (see the Municipal bond market data and characteristics section in the Methods).

We have thus identified 1,880 green bonds issued by 189 distinct issuers on the municipal market. These represent an outstanding value of US$12 billion. To this sample of green bonds, we have associated a sample of conventional bonds comprising 36,000 securities issued by the same set of issuers, which amounts to a total value of US$170 billion. We have then scraped comprehensive issuance and transaction data for these two sets of bonds (see the Municipal bond market data and characteristics section in the Methods). The resulting data set contains approximately 1.6 million data points.

The yield of a bond is the total rate of return an investor realizes on a bond, given on the one hand the price he pays and on the other hand the coupon and principal payments he receives. A peculiarity of municipal bonds is that they are often callable; that is, they have a call option attached that allows the issuer to redeem the bond at each coupon date after the first call date until the final maturity date. To keep prices and yields of bonds comparable, we priced out the value of this option and focus on the 'straight' price of each bond and the ensuing yield to maturity (see the Early redemption date section in the Methods).

The yield differential between green and conventional bonds is the central focus of our analysis. Each transaction of a bond provides an observation of a yield for a certain (remaining) maturity. Yield curves allow aggregation of this information through a representation of the relationship between maturities (on the horizontal axis) and yields (on the vertical axis). Hence, to provide a synthetic overview of the relationship between green and conventional bond yields, we have constructed, using the Svensson method[14], yield curves aggregating the yield data of green and conventional bonds for different rating groups respectively (see the Creating a comparable agency rating scale and the Constructing yield curve sections in the Methods). The yield curves are displayed in Fig. 1. They exhibit a 'standard' shape (that is, they are upward sloping), indicating that investors are demanding a higher rate of return to compensate for the increased (default) risk associated with longer-term investments.

Concerning the comparative statics between green and conventional bonds, the main observation in the plot of Fig. 1 is that the green bond yield curve is systematically below the conventional bond one. This means that investors require, on average, a lower interest rate to invest in green bonds. We investigate below whether this green bond premium is a fundamental feature of the market, explained by the existence of a specific demand for green bonds, or whether it is an artefact of an uneven distribution of characteristics among green and conventional bonds, which might explain the difference in yield through, for example, the differences in creditworthiness of the issuers.

Another observation is that the spread between conventional and green bonds widens with the maturity. An essentialist interpretation of this finding would be that investors perceive green bond projects aligned with sustainable development objectives as less risky in the long term and therefore requiring a lower interest rate when compared to conventional bonds with equivalent maturity. As for the existence of the spread per se, the widening spread might also be explained by differences in the intrinsic characteristics of the two samples of bonds, independently of their green or conventional nature.

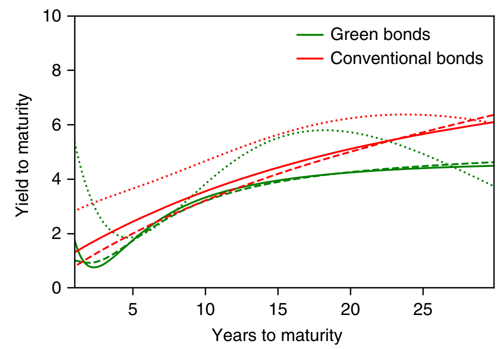

Fig. 1 | Comparison of yield curves. Yield curves, representing the relation between the yield (*y* axis) and the time to maturity (*x* axis) for samples of green and conventional bonds (solid line: overall; hashed line: A rating; dotted line: B rating).

Determinants of the yields of municipal bonds. To investigate quantitatively the relationship between the yields of green and conventional bonds, we first build a regression model to characterize the quantitative determinants of the yield structure. Our data consist of a set of transactions for each bond. Each transaction can be interpreted as an assessment of the market of the value/yield of a bond given its: remaining days to maturity and possible early redemption dates; the (current) characteristics of the bond and its issuer; and the current state of the credit market. The large number of transactions in the data set implies that one has, on average, 1,000 price observations for each bond. This provides abundant information about the impact of observable characteristics on the yield of a bond and helps one to isolate the impact of the green label. Nevertheless, the caveat remains that two bonds, even from the same issuer, are never perfectly comparable, as they might differ in some quantitative (for example, size or timing) and qualitative dimensions (embedded in particular in the documentation associated with the bond). We specify our regression model to exploit the maximal amount of information to overcome this difficulty (see the Specification of the regression section in the Methods).

The results are presented in Table 1. All of the coefficients are statistically significant, and the results are consistent with theoretical relationships established in market finance. Namely, the yield increases with the benchmark market rate (treasury) and with the risk, measured via days to maturity, the rating class of the bond or the outstanding debt in the state (local_debt and state_debt). It decreases with liquidity (freq) and with positive macroeconomic indicators (realgrowth and population) (see the Specification of the regression section in the Methods for a detailed interpretation of the results).

Oaxaca–Blinder decomposition. To determine whether there actually exists a green premium or whether the difference in yields identified above can be explained by other observable characteristics of the bonds, we perform an Oaxaca–Blinder decomposition of the yield spread between green and conventional bonds. The Oaxaca–Blinder decomposition was initially introduced to quantify gender-based discrimination in the labour market[11,12]. In our context, it allows one to disentangle the impacts on the yield of the

Table 1 | Results of the regression of the yields to call of green bonds, conventional bonds and the pooled data sample

	Dependent variable		
	Yield to call		
	Green bonds	Conventional bonds	Pooled data
dtm	0.287***	0.538***	0.530***
	(0.003)	(0.001)	(0.001)
amount	0.003**	−0.032***	−0.031***
	(0.001)	(0.001)	(0.001)
paissuance	−0.099***	0.028***	0.026***
	(0.005)	(0.001)	(0.001)
freq	−0.009***	−0.013***	−0.013***
	(0.003)	(0.001)	(0.001)
ratingA	−1.639***	−0.048***	−0.036***
	(0.468)	(0.002)	(0.002)
ratingB	−1.418***	0.676***	0.626***
	(0.468)	(0.005)	(0.004)
treasury	1.131***	0.548***	0.556***
	(0.005)	(0.001)	(0.001)
broker	0.063***	0.105***	0.103***
	(0.003)	(0.001)	(0.001)
local_debt	−0.149***	0.053***	0.057***
	(0.005)	(0.001)	(0.001)
state_debt	−0.076***	0.063***	0.072***
	(0.005)	(0.001)	(0.001)
realgrowth	−4.217***	−3.237***	−2.996***
	(0.248)	(0.038)	(0.038)
population	−0.185***	−0.759***	−0.738***
	(0.056)	(0.020)	(0.020)
Constant	4.833***	1.279***	1.183***
	(0.465)	(0.087)	(0.083)
Observations	70,398	1,543,394	1,613,792
Log likelihood	−34,872.340	−1,730,589.000	−1,801,736.000
Akaike information criterion	69,774.680	3,461,207.000	3,603,502.000
Bayesian information criterion	69,912.110	3,461,391.000	3,603,686.000

The yield increases with the benchmark market rate (treasury) and the risk, measured via days to maturity (dtm), the rating class (ratingA and ratingB) of the bond or the outstanding debt in the state (local_debt and state_debt). It decreases with liquidity (freq) and with positive macroeconomic indicators (realgrowth and population). Further information regarding the regression parameters can be found in the Methods. The standard errors are displayed in the parentheses below the parameter estimates. The parameter estimates are marked, corresponding to their significance levels, with *$P<0.1$; **$P<0.05$; ***$P<0.01$.

observable characteristics of the issuers and of the market environment, from the effect of the green label per se (see Oaxaca–Blinder basic two-fold decomposition section in the Methods).

The results of the Oaxaca–Blinder decomposition are displayed in Table 2 with conventional bonds as the reference group. The overall mean spread in returns between conventional and green bonds is 0.23; that is, 23 basis points. This difference is statistically significant over the drawn bootstrap sample. As already observed in Fig. 1, the yield to maturity is thus on average higher for conventional bonds than for green bonds. The twofold Oaxaca–Blinder decomposition method allows us to separate this spread into an 'explained' part, which is due to differences regarding characteristics (fundamentals) between the two groups, and an 'unexplained' part, which is not due to fundamentals and would signal the existence of a 'green' premium. In other words, the 'unexplained' component measures how the average yield on green bonds would change if they were evaluated by the market the same way as conventional bonds are.

The parameters estimated for the 'explained' and 'unexplained' parts are 0.308 and −0.078, respectively. All parameter estimates are statistically significant. This implies that, on the basis of the fundamentals alone, the spread between the average yield of conventional and green bonds should have been 30.8 basis points. This is higher than the observed average spread of 23 basis points. The difference (that is, the unexplained part) is the impact of the green nature of the bond per se. Over the time window considered, this impact has been negative and amounted to 7.8 basis points. In other words, if green bonds had been evaluated as conventional bonds, they would have yielded an, on average, 7.8 basis point lower return.

These results have two main implications. First, the market has required a lower yield from municipal green bonds because of their fundamental characteristics regarding creditworthiness, not because of their green nature. In other words, green bonds have been issued by municipalities that appear less risky to the market. This is further emphasized by the signs of the coefficients in the detailed decomposition of the 'explained' part. The parameters with a positive sign (that is, those that contribute to the difference in yields) are characteristics of the risk related to the issuer (amount, paissuance, ratingA, ratingB, treasury, state_debt, realgrealgrowth and population). The parameters with a negative sign (that is, these that ought to reduce the difference in yields) rather are relative to the specifics of the bonds (dtm, freq, broker and local_debt). Second, all other things being equal, the market has discriminated against green bonds. It has requested on average a higher yield (by 7.8 basis points) for green bonds than it would have demanded from a conventional bond with equivalent characteristics.

Evolution over time. The previous results represent an average over time. If one accounts for the evolution over time of the relative yields, a more complex picture emerges. In this respect, Table 3 reports the results of the yield decomposition performed, with the same specification as above, on yearly subsets from 2010 to 2016. One can clearly distinguish two periods: the first five years of the market on the one hand and the two last years on the other hand. During the first period, the yield on conventional bonds was lower than this of green bonds (the difference coefficient is negative), and there was a negative premium on green bonds (the unexplained part is negative). During the second period, 2011, the yield on conventional bonds has been higher than that of green bonds, and there has been a positive premium on green bonds. These results are consistent with those of the preceding section, but they imply that the aggregate difference in yields is mainly driven by the second period while the aggregate premium is driven by the characteristics of the first period.

Hence, the average credit quality of green bonds, as measured by the return required by the market, has increased over time as well as the premium offered by the market (over comparable conventional bonds). In the last two years, the premium has even turned positive. This suggests that the premium could be interpreted as a measure of the reputation effect on green bonds. In the first period, green bonds were on average of lower credit quality than conventional bonds. Hence, the market might have developed a negative bias towards green bonds that materialized through a negative premium, a negative reputation effect. As the credit quality of green bonds increased over time, so did their reputation and they eventually gained a positive premium (of 38 basis points in 2016).

Table 2 | Oaxaca–Blinder decomposition of the difference between the yields of green and conventional bonds

	Est.	s.e.m.	*t*	.25 pct	.975 pct	*P* > |*t*|
Overall						
Difference	0.23	0.0158	150.2701	0.2342	0.2405	0
Explained	0.308	0.0161	195.8903	0.3122	0.3186	0
Unexplained	−0.078	0.0044	−175.8092	−0.0789	−0.0772	0
Explained — detail						
(Intercept)	-	-	-	-	-	-
dtm	−0.0625	0.0029	−213.0292	−0.0619	−0.0608	0
amount	0.0012	2×10^{-4}	56.6904	0.0012	0.0013	0
paissuance	0.006	5×10^{-4}	130.4346	0.006	0.0062	0
freq	−0.0013	1×10^{-4}	−107.4099	−0.0013	−0.0013	0
ratingA	0.0117	8×10^{-4}	142.8974	0.0116	0.0119	0
ratingB	0.0283	0.0021	139.02	0.0285	0.0293	0
treasury	0.1386	0.0074	189.4613	0.139	0.142	0
broker	−0.0062	4×10^{-4}	−172.6524	−0.0064	−0.0063	0
local_debt	−0.0057	0.001	−51.0425	−0.0055	−0.0051	0
state_debt	0.0189	0.0016	119.4628	0.0192	0.0198	0
realgrowth	0.0096	4×10^{-4}	223.6931	0.0096	0.0098	0
population	0.1695	0.006	288.5611	0.1708	0.1731	0
Unexplained — detail						
(Intercept)	−0.1724	0.0213	−83.3241	−0.182	−0.1735	0
dtm	1×10^{-4}	0	25.122	1×10^{-4}	1×10^{-4}	0
amount	0	0	6.8132	0	0	0
paissuance	-2×10^{-4}	0	−91.4547	-2×10^{-4}	-2×10^{-4}	0
freq	-1×10^{-4}	0	−58.7569	-1×10^{-4}	-1×10^{-4}	0
ratingA	0.0675	0.0165	43.6223	0.0689	0.0754	0
ratingB	0.0139	0.0027	55.1218	0.0143	0.0153	0
treasury	−0.0544	0.0051	−104.4149	−0.0544	−0.0524	0
broker	5×10^{-4}	1×10^{-4}	86.0511	5×10^{-4}	5×10^{-4}	0
local_debt	0.1051	0.0094	109.4367	0.1011	0.1049	0
state_debt	−0.0334	0.0045	−72.5277	−0.0338	−0.032	0
realgrowth	−0.0018	2×10^{-4}	−76.0872	−0.0017	−0.0017	0
population	−0.0027	6×10^{-4}	−40.2473	−0.0027	−0.0024	0

The decomposition determines which part of the difference in yields can be explained by the regressors (the explained part) and which part characterizes the green premium (the unexplained part). For both parts, the contribution of each regressor is provided in the lower part of the table. A precise description of the regressors can be found in the Methods. The decomposition results are based on a sample of 1,543,394 conventional and 70,398 green bonds and 100 bootstrap iterations. pct; percentiles.

Table 3 | Evolution over time of the difference between the yields of green and conventional bonds, together with the explained and unexplained ('green premium') part of this difference

	2010	2011	2012	2013	2014	2015	2016
Difference	−1.3156	−1.0871	−0.8316	−0.7329	−0.1892	0.2706	0.3974
Explained	−0.2881	−0.355	−0.3026	−0.0036	0.1482	0.0902	0.0221
Unexplained	−1.0275	−0.7321	−0.529	−0.7293	−0.3374	0.1804	0.3753

Conclusion

We have investigated the differences in the yield term structure between green and conventional bonds on the US municipal bonds market. There is on average a positive and statistically significant spread between conventional and green bonds. This spread can be explained by differences in the fundamental characteristics of conventional and green bonds. Issuers of green bonds are in general more creditworthy, and have more robust economic fundamentals. This could be interpreted as an instance of an environmental Kuznets curve. A decomposition of the difference between the yields using the Oaxaca–Blinder decomposition, however, shows that issuers of green bonds have historically faced a negative premium on the US municipal bond market. All other things being equal, the market has required a higher yield from green bonds than from conventional ones. However, the situation has shifted in recent years, where, following the rise of the credit quality of green bonds on the municipal market, the premium has eventually turned positive. Although these last results suggest that green bonds have become very attractive to investors in recent years, the seemingly important effect of reputation externalities suggests caution about the existence of a large specific demand for green bonds or the willingness of investors to 'pay for green'.

These findings have important implications for the expansion of the green bond market and more broadly for climate finance. Indeed, if the premium on green bonds is related to the average credit quality of issuers, an expansion of the market towards lower-tier creditors might revert the positive trend on the premium and impact the financing conditions of all the issuers. The issue is of particular concern because an important part of the financing needs for mitigation, and even more so for adaptation, concerns developing countries and small-scale projects[2], which appear more risky to the market. A conventional solution to the issue is the pooling of risks (for example, through structured bonds). On the green bond market, this role has been played to a large extent by large multilateral development banks such as the World Bank. An important advantage of multilateral development banks in this respect is that they provide both financial and fiduciary guarantees on the green usage of the proceeds. However, there is a limit to the expansion of the balance sheet of multilateral development banks. Private financial institutions that could provide similar services in terms or risk management have less capacity and credibility to certify the green nature of projects. An important dimension of green bonds for investors is the precise information about the social and environmental impact of their investments[15]. This component would be partly lost through pooling. The ongoing development of green rating agencies might offer a solution to this issue. An alternative, related to the development of green crowdfunding[16], might be the decentralized evaluation and labelling of projects by communities of investors.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-017-0062-0.

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Author contributions

On the basis of an idea of A.M., A.K. and A.M. designed the research and wrote the paper. A.K. designed and performed the quantitative analysis.

Competing interests

The authors declare no competing financial interests.

Additional information

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Methods

Data. *Bloomberg Green Bond Database.* Bloomberg tags a bond as green if the documentation provided by the issuer indicates that: the proceeds are to be used consistently with the Green Bond Principles (that is, 'towards projects or activities that promote climate change mitigation or adaptation or other environmental sustainability purposes'[5]); and the issuer intends to meet certain criteria concerning management of proceeds, transparency and/or reporting. Although Bloomberg reviews the documents published by the issuer in this perspective, there is not necessarily a second opinion on the labelling of the bond or an ex post monitoring of the use of proceeds. It is also the case that only bonds that use 100% of the proceeds in accordance with the principles are labelled as green. Hence, some bonds might be unlabelled although part, or the majority, of the proceeds, is used for green projects. Despite these caveats, alternative databases, such as the climate bonds initiative[17], use a similar methodology and have very similar coverage[8]. Furthermore, Bloomberg is one of the leading data providers to the financial industry, and its labelling is, therefore, per se, a strong signal to investors about the green nature of the bond.

Municipal bond market data and characteristics. Municipal bonds are bonds issued by US local governments (that is, below the federal level). With an outstanding value of approximately US$3 trillion, the municipal bond market represents a non-negligible share of the global bond market. The market is well diversified both on the demand side and on the supply side with close to 100,000 issuers covering a range of credit ratings, maturities, sectors and territories[18,19]. The average rating is much higher and the share of speculative-grade bonds much lower on the municipal than on the corporate bond market. Therefore, the municipal market can be considered as representative of the investment landscape of a long-term investor. Moreover, municipal bonds have two important advantages regarding sample size and data availability: they are the largest category within the Bloomberg Green Bond Database, and the Municipal Securities Rulemaking Board (MSRB) provides a comprehensive data set about issuance and transactions on the US municipal bonds market[20]. Hence, although the caveat concerning the difference in size between the conventional and green bond market remains, the municipal market seems to us to have the most appropriate scope and data availability to perform a comparative analysis of the yield of green and conventional bonds.

Via the Bloomberg Terminal, we gathered the CUSIP identification numbers of 1,880 securities labelled as green bonds in the municipal bond market. This, in turn, permitted us to scrape issuance and trading data (around 2.1 million transactions) from the website of the Electronic Municipal Market Access (EMMA)[20] for 36,000 bonds from the same set of issuers as the original 1,880 securities labelled as green bonds. This allowed us to compare the yield term structure of conventional and green bonds respectively of the same set of issuers in the municipal bond market.

For each bond, the database provides a unique identifier, called CUSIP, the name of the issuer, the principal amount at issuance (that is, the total volume issued), the nominal interest rate (that is, the face value of the coupon rate), the maturity date (that is, the date on which the principal amount of the bonds becomes due) and the rating of the bond by one of the established rating agencies (Moody's, S&P, Fitch or Kroll). In addition to the characteristics of the bond, the data set provides for each transaction the price at which the bond was traded, the amount traded, the trade type (that is, whether the parties to the trade are finance professionals or private customers), the yield and the timestamp. More precisely, the data base is organized as follows:

Trade Date/Time: The time and date on which a legally binding agreement was reached between the buyer and seller of the securities.

Settlement Date: The date on which the transaction is completed, which is when final payment for the bonds and transfer of ownership of the bond occurs. Transactions in the secondary market typically settle three business days after the trade date.

- CUSIP: The CUSIP9 identification number for the securities.
- Security Description: The name of the issuer and the issue description.
- Maturity Date: The date on which the principal amount of the bonds becomes due.
- Interest Rate: The stated interest (or 'coupon') rate for fixed-rate securities.
- Price: The purchase price of the security.
- Yield: The yield to worst based on the settlement date, price, interest rate on the security and the remaining period until the maturity or the earlier redemption date.
- Calculation Date and Price: The date and price used by the MSRB to compute the yield.
- Trade Amount: The volume traded in the respective transaction (the principal amount times the number of bonds sold/bought).
- Principal Amount at Issuance: The total volume of an issued bond (the total number of bonds issued times the principal).
- Trade Type: The type of transactions (that is, whether the security was bought from a broker/dealer or bank, or if the security was sold by a customer to a broker/dealer or bank, or if the deal was between a broker/dealer or a bank).

Agency Rating: From the EMMA website, we also downloaded issuer ratings from the rating agencies Moody's, Standard & Poor's, Fitch and Kroll. Since only one rating from one of the rating agencies is available for most of the bonds, we had to find a common scale to combine the ratings from the different agencies for our econometric analysis. The method is described in the Creating a comparable agency rating scale section.

Transactions with missing yield information or other apparent mistakes were excluded from the analysis. This brings down the number of data points to 1.6 million.

Early redemption date. A property unaccounted for in the data scraped from the EMMA website is the early redemption date, normally ten years after the date of issuance applicable for the majority of longer running bonds issued in the municipal bond market. The early redemption date is unfortunately not supplied with the data on the EMMA website. It comes only with the legal document describing the contractual details of the bonds issuance. Systematically parsing this information would represent a very complicated task. We instead exploit the fact that the EMMA website supplies us with information about the exact trading and settlement date, the transaction price and the corresponding yield to worst, which, in fact, corresponds to the yield to call, and thus the early redemption date. Knowing the formulae used by the MSRB to compute the yield to worst (call), we can infer the days from the respective trade date to the early redemption date. The MSRB and the corresponding issuing entities use the following two formulae to compute the yield to worst (call) (ref. [21], p. 251). For bonds with a maturity longer than the period between interest payments:

$$P=\left[\frac{\mathrm{RV}}{\left(1+\frac{Y}{M}\right)^{N-1+\frac{E-A}{E}}}\right]+\left[\sum_{K=1}^{N}\frac{100\times\frac{R}{M}}{\left(1+\frac{Y}{M}\right)^{K-1+\frac{E-A}{E}}}\right]-\left[100\times\frac{A}{B}\times R\right] \quad (1)$$

For bonds with a maturity shorter than the period between interest payments:

$$P=\left[\frac{\frac{RV}{100}\times\frac{R}{M}}{1+\left(\frac{E-A}{E}\times\frac{Y}{M}\right)}\right]-\left[\frac{A}{B}\times R\right] \quad (2)$$

where A is the number of accrued days from the beginning of the interest payment period to the settlement date, B is the number of days in the year, E is the number of days in the interest payment period in which the settlement date falls, M is the number of interest payment periods per year standard for the security involved in the transaction, P is the dollar price of the security for each 100 par value (divided by 100), R is the annual interest rate (expressed as a decimal), RV is the redemption value of the security per 100 par value and Y is the yield price of the transaction (expressed as a decimal). The numbers of days were computed in accordance with the provisions of the MSRB (ref. [21], Rule G.33 on pp. 252–259).

Creating a comparable agency rating scale. For most of the bonds scraped from the EMMA website, only one rating from one agency is available. Since we need a single variable for each bond reflecting agency ratings for our econometric analysis, we had to create a common scale for the ratings from Moody's, S&P, Fitch and Kroll, respectively. Conventional tables comparing rating scales among agencies have been used in this respect in previous studies[22,23].

Supplementary data. We supplemented the data from the EMMA website with information about the yearly state- and local-level government debt data, the gross state product, the state population and real growth of the gross state product from the US Census Bureau[24].

We further downloaded daily rates of US Treasury bonds[25] for customary maturities (from 1 month to 30 years) for the periods in which transaction data of our municipal bond sample are available (2005–2016). We used this point information of US Treasury rates to construct daily yield curves via spline interpolation and to compute benchmark rates for each transaction and the respective bond's remaining days until maturity in our sample.

Quantitative analysis. *Constructing yield curve.* For the conducted decomposition of the mean between conventional and green bonds, a yield to maturity value is needed, which takes into account the early redemption (call) date (which is a feature of most of the municipal bonds under consideration). The information that comes with each bond transaction is the maturity date, the trade or settlement date respectively, the price and the corresponding yield to worst (call). We use this information with the formulae (1) and (2), respectively, to infer the actual early redemption date. This allowed us to set up a callability schedule of each bond under consideration and to compute a yield to maturity taking into account a potential early redemption date. The necessary computations were performed using the Python library QuantLib[26]. For the sake of simplicity, this yield corrected for the early redemption option will be referred to as yield to call (ytc). It is our independent variable in the process of decomposing the spread between green and conventional bonds in the municipal bonds market.

We construct yield curves from the ytc values computed for each transaction according to the description above, using the Svensson method[14]. In doing so, we assume that the ytc values, computed for each bond at each point in time it was traded, are par rates. We thus assume to have bonds with coupon rates equal to the ytc, issued at a specific trade date, maturing at the respective maturity date with, for the majority of bonds, optional redemption after a certain period of time. This allows us to construct yield term structure plots for yield-to-maturity rates and to visually inspect the difference between green and conventional bonds in our sample from the municipal security market.

Specification of the regression. Our estimation of the yield is constructed as follows.

We first consider a set of variables that refer to the characteristics of the bond: dtm (the number of days to maturity); paissuance (the principal amount at issuance; that is, the total nominal value of the emission); and freq (the trading frequency, computed as the number of transactions of the bond within the past 30 days). It serves as a proxy for liquidity.

Second, we consider a set of variables that refer to the characteristics of the transaction: amount (the total nominal value exchanged in the transaction); and broker (a dummy variable indicating whether the transaction was conducted via a broker).

Third, we consider a set of variables that refer to the creditworthiness of the issuer: on the one hand, the issuer-specific random intercepts included in the model, to capture unobserved issuer effects, and, on the other hand, ratingA and ratingB, which are dummy variables indicating whether a bond is in the group of A- or B-rated bonds, respectively. The dummy variable for the large group of unrated bonds is omitted here. It can be understood as the base category.

Fourth, the state of the credit market is captured by the variable 'treasury' (the Treasury rate of the same maturity as the bond). Finally, we consider a set of variables that capture the macroeconomic conditions in the state of the issuer: realgrowth (the real growth rate of the gross state product; population (the population of the state); and local_debt and state_debt (the level of outstanding debt at the municipal and state level, respectively). We thus estimate the following linear mixed-effects models with random intercepts:

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$$\begin{aligned} \text{ytm}_{ij} = \; & \beta_0 + \beta_{0j} + \beta_1 \text{dtm}_i + \beta_2 \text{amount}_i + \beta_3 \text{paissuance}_i + \beta_4 \text{freq}_i \\ & + \beta_5 \text{ratingA}_i + \beta_6 \text{ratingB}_i + \beta_7 \text{treasury}_i + \beta_8 \text{broker}_i \\ & + \beta_9 \text{local\_debt}_i + \beta_{10} \text{state\_debt}_i \\ & + \beta_{11} \text{realgrowth}_i + \beta_{12} \text{population}_i + \varepsilon_{ij} \end{aligned} \quad (3)$$

Here i denotes the observation index and j identifies the issuer. Following a previous study[27], we estimate the linear model on three different data (sub)sets: green bonds, conventional bonds and the pooled data set.

Oaxaca–Blinder basic two-fold decomposition. The Oaxaca–Blinder decomposition builds on two independent regressions of the variable under consideration, the yield in our context, for the two groups whose relationship one wants to analyse, green and conventional bonds in our context. One can then choose one of the subsamples as the reference group and decompose the difference in average yields between the reference and the alternative group into a data-related effect (E) and a coefficient-related effect (C).

The data-related effect corresponds to the difference obtained if average yields are computed for the two subgroups using the reference group's coefficients. That is, it measures how much of the difference is explained by the data (given the choice of a reference group). The coefficient-related effect corresponds to the difference obtained if the average yield for the non-reference group is computed with its proper coefficients, on the one hand, and the coefficients of the reference group, on the other hand. It hence measures the part of the difference that cannot be explained by the data and may thus be attributed to discrimination.

The decomposition method used in this paper is an extension of the original Blinder–Oaxaca approach[11,12]. Let N and K be the numbers of observations and parameters, respectively, then Y is the $N\times1$ vector representing the explained variable, X is the $N\times K$ data matrix and β is the $K\times1$ parameter vector. It is assumed that a function $F(\cdot)$ maps a linear combination of X ($X\beta$) to Y (ref. [28]; p. 558):

$$Y = F(X\beta) \quad (4)$$

The properties of $F(\cdot)$ depend on the respective estimation technique. In the context of this paper, we will use linear mixed-effects models with random intercepts for each group (issuer). The goal is to decompose the mean difference between two groups A and B ($\bar{Y}_A - \bar{Y}_B$) into a data-related effect (E), on the one hand, and a coefficient-related effect (C), on the other hand:

$$\widehat{D} = \bar{Y}_A - \bar{Y}_B = \overline{F(X_A\beta_A)} - \overline{F(X_B\beta_B)} \quad (5)$$

$$= \underbrace{[\overline{F(X_A\beta_A)} - \overline{F(X_B\beta_A)}]}_{E} + \underbrace{[\overline{F(X_B\beta_A)} - \overline{F(X_B\beta_B)}]}_{C} \quad (6)$$

The notation $\bar{Y}_B = \overline{F(X_A\beta_A)}$ and $\bar{Y}_B = \overline{F(X_B\beta_B)}$ refers to the mean outcomes of groups A and B respectively. Equivalently, $F(X_A\beta_B)$ corresponds to the mean outcome computed using data from group A with coefficients from group B. The intuition behind the Oaxaca–Blinder decomposition is the following: while for component E, group-specific subsets of the data set but the same coefficients are used, in component C, the difference is computed using the same data subset but group-specific coefficients. Component E thus corresponds to measuring the impact of the data on the difference in outcomes assuming that the relationship (the coefficients) between the data and the outcome is invariant with respect to the different groups. For the C component, this is the other way around: using the same subset of the data but group-specific coefficients allows one to isolate the difference in outcome that is due to a difference in coefficients and thus the way the data relates to the outcomes. The idea behind this sort of decomposition was initially to investigate to which extent the difference between wages of men and women is related to discrimination. In this context, E comprises the part of the wage gap that is explainable by the data as for example by differences of education, work experience and so on, while C captures effects that are not explainable by the data and might be due to discrimination.

A decomposition of this sort is, of course, sensitive to the choice of the reference group. In equation (5), the reference group is assumed to be group A. Alternative specifications for the vector of coefficients β_R (ref. [29]) can be used and equation (5) modified accordingly:

$$\widehat{D} = [\overline{F(X_A\beta_R)} - \overline{F(X_B\beta_R)}] + [\overline{F(X_B\beta_R)} - \overline{F(X_B\beta_B)}] \quad (7)$$

In the literature, different suggestions for β_R can be found[27,30,31]. We have used both the reference group method as well as the method proposed previously[27], for which the coefficient vector is based on a regression on pooled data from groups A and B. Results are qualitatively similar if conventional bonds or the pooled sample is used as the reference group.

Details of the Oaxaca–Blinder decomposition. Expression (7) can further be decomposed to the contribution of each parameter thus the weight of each parameter within both components, namely $W^i_{\Delta X}$ as far as the endowment effects (E) are concerned and $W^i_{\Delta\beta}$ for the coefficient effects (C):

$$\widehat{D} = \sum_{i=1}^{K} W^i_{\Delta X} [\overline{F(X_A\beta_R)} - \overline{F(X_B\beta_R)}] + \sum_{i=1}^{K} W^i_{\Delta\beta} [\overline{F(X_B\beta_R)} - \overline{F(X_B\beta_B)}] \quad (8)$$

Following a previous study[32], mean characteristics are used to rewrite (7):

$$\widehat{D} = [F(\overline{X}_A\beta_R) - F(\overline{X}_B\beta_R)] + [F(\overline{X}_B\beta_R) - F(\overline{X}_B\beta_B)] + R_M \quad (9)$$

where

$$\begin{aligned} R_M = \; & [\overline{F(X_A\beta_R)} - \overline{F(X_B\beta_R)}] + [\overline{F(X_B\beta_R)} - \overline{F(X_B\beta_B)}] \\ & - [F(\overline{X}_A\beta_R) - F(\overline{X}_B\beta_R)] - [F(\overline{X}_B\beta_R) - F(\overline{X}_B\beta_B)] \end{aligned}$$

Then the C and the E components are linearized around $X_A\beta_R$ and $X_A\beta_B$ by a first-order Taylor expansion respectively.

$$\begin{aligned} \widehat{D} = \; & \frac{\delta F(\overline{X}_A\beta_R)}{\delta(\overline{X}_A\beta_R)} (\overline{X}_A\beta_R - \overline{X}_B\beta_R) + \frac{\delta F(\overline{X}_B\beta_B)}{\delta(\overline{X}_B\beta_B)} \\ & \times (\overline{X}_B\beta_R - \overline{X}_B\beta_B) + R_M + R_T \\ = \; & (\overline{X}_A - \overline{X}_B)\beta_R f(\overline{X}_A\beta_R) + \overline{X}_B(\beta_R - \beta_B) f(\overline{X}_B\beta_B) + R_M + R_T \end{aligned} \quad (10)$$

where

$$\begin{aligned} R_T = \; & [F(\overline{X}_A\beta_R) - F(\overline{X}_B\beta_R)] + [F(\overline{X}_B\beta_R) - F(\overline{X}_B\beta_B)] \\ & - (\overline{X}_A - \overline{X}_B)\beta_R f(\overline{X}_A\beta_R) + \overline{X}_B(\beta_R - \beta_B) f(\overline{X}_B\beta_B) \end{aligned}$$

Using equation (10), one can express the weights $W^i_{\Delta X}$ and $W^i_{\Delta\beta}$, respectively.

$$W^i_{\Delta X} = \frac{(X^i_A - X^i_B)\beta^i_R f(\overline{X}_A\beta_R)}{(X_A - X_B)\beta_R f(\overline{X}_A\beta_R)} = \frac{(X^i_A - X^i_B)\beta^i_R}{(X_A - X_B)\beta_R} \quad (11)$$

$$W^i_{\Delta\beta} = \frac{\overline{X}^i_B(\beta^i_R - \beta^i_B) f(\overline{X}_B\beta_B)}{\overline{X}_B(\beta_R - \beta_B) f(\overline{X}_B\beta_B)} = \frac{\overline{X}^i_B(\beta^i_R - \beta^i_B)}{\overline{X}_B(\beta_R - \beta_B)} \quad (12)$$

The weights (11) and (12) have to sum up to one: $\sum_{i=1}^{K} W^i_{\Delta X} = 1$ and $\sum_{i=1}^{K} W^i_{\Delta\beta} = 1$.

Statistical properties of the estimated decomposition parameters. The statistical properties of the decomposition parameters estimated along the methodology described above are evaluated by means of drawing random bootstrap samples in 100 iterations. The sole restriction applied to the random sampling in the bootstrapping procedure is the presence of the same issuers in both sampling strata (conventional and green bonds). Otherwise, the application of the Oaxaca–Blinder decomposition is, in the presence of issuer-specific (random) intercepts, not possible.

Data availability. The data on municipal bonds are available, in an unstructured format, from the MSRB website[20]. Due to the terms and conditions of the MSRB, we can not make them publicly available in a structured format but they are available from the authors upon reasonable request. The supplementary data with information about the different federal states from the US Census Bureau and the daily rates of US Treasury bonds are available from a previous study[33].

Code availability. The Python and R code to analyse the data are available from a previous study[33].

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