Attribute associations of municipal green bond yield spreads: A demand perspective

Mohammad Hadi Sehatpour[a], Marta Campi[b], Christina S. Nikitopoulos[a,*], Gareth W. Peters[c], Kylie-Anne Richards[a,d],

[a] *University of Technology Sydney, Finance Discipline Group, UTS Business School, PO Box 123 Broadway NSW 2007, Australia*

[b] *Institut Pasteur, Université Paris Cité, Inserm, Institut de l'Audition, IHU reConnect, F-75012 Paris, France*

[c] *University of California Santa Barbara, Department of Statistics and Applied Probability, Santa Barbara CA 93106-3110, USA*

[d] *Future Fund Management Agency, Australia's Sovereign Wealth Fund, Locked Bag 20010 Melbourne VIC 3001, Australia*

Abstract

Investor demand and bond structuring attributes jointly shape the pricing of green municipal bonds. We introduce a yield-to-maturity–based approach to measuring municipal green bond spreads and apply it to the California market between 2016 and 2024. These spreads are on average positive but turned negative after 2022. Using Association Rule Learning, we identify that positive spreads are associated with taxable, at-par, callable, and long-maturity bonds, whereas negative spreads are linked to more complex combinations including low spreads at issuance, non-callable, tax-exempt, at-premium, and short-maturity bonds. We further demonstrate that international demand matters: stronger bidding in Japanese Treasury auctions systematically raises issuance yields for U.S. municipal green bonds, particularly in higher-order attribute groups. These results show how structuring attributes and cross-border demand jointly shape green bond pricing, offering practical insights for issuers seeking to optimize financing costs and for investors navigating sustainability-driven markets.

Keywords: green bonds, municipal bonds, yield to maturity, demand, tax status, callability

JEL: C11, E43, E44, G12, Q51, Q56

*Corresponding author christina.nikitopoulos@uts.edu.au

1. Introduction

The issuance of green bonds has been steadily increasing over the years. At the end of March 2025, the cumulative aligned issuance of green bonds reached USD 3.7 trillion, representing approximately 62% of the total market, while the overall volume of green, social, sustainability, and sustainability-linked debt (GSS+) exceeded USD 5.9 trillion (Climate Bonds Initiative, 2025). However, this significant growth of the green bond market has not been done homogeneously. Initially, short-term bonds were issued due to uncertainty and limited demand. Over time, issuances expanded to longer maturities, particularly as major state-based entities joined the market. Recently, municipal issuers focusing on intermediate-term structures have become more prominent, covering a broader range of projects under the "use of proceeds" (UOPs)[1] (Doran and Tanner, 2019; OECD, 2017). The current demand for green bonds also far exceeds their supply, with these constraints stemming from supply issues, since most issuances have been oversubscribed (Brennan and MacLean, 2018). Thus, challenges such as the supply–demand imbalance, insufficient liquidity in secondary markets, and the underdeveloped yield curve for green bonds, leading to a lack of instruments across various tenors,[2] underscore the market's immaturity and the hurdles that must be overcome for its maturation (Shinde, 2021; OECD, 2017).

As the green bond market expands, investors need to be equipped with the tools and understanding necessary to navigate the complexities of these markets. In light of the unique green attributes embedded in these financial instruments, the performance of green bonds relative to conventional bonds, captured by their spread, attracts significant attention from academics, industries, and policy makers. The spread serves as a critical indicator that can provide information on investor sentiment, risk assessment, and issuer behavior (Fang et al., 2023). In conventional bonds, the risk premium captures information related to structuring, time to maturity, and default risk, while measures of risk premium in green bonds may also

[1] UOP is a distinct feature of green bonds (compared to conventional bonds) and refers to the explicit allocation of funds raised from a green bond expected to fund green-related projects, such as energy efficiency and biodiversity conservation.

[2] While some green bonds now price on or inside their yield curves, the market is not yet as robust as for conventional bonds. This underdevelopment can make it challenging to accurately price green bonds and assess their performance relative to conventional bonds.

reflect the effectiveness of green UOPs over long time periods and green defaults. Green bond spread also mirrors investor demand for environmentally conscious investments and the efficacy of policy interventions to enhance the attractiveness and effectiveness of green bonds, thus informing investment strategies and regulatory frameworks.[3]

In this paper, we propose a novel approach for calculating green bond spreads based on yields to maturity (YTM). We compute non-parametric green bond spreads based on a tenor-specific approach that uses the YTM of all available green bonds each day. Using daily data from California municipal green bonds between 2016 and 2024, we calculate green bond yield spreads, capturing the spread of green bonds relative to the U.S. risk-free rate, represented by the U.S. Treasury par curve. California's leadership in environmental policy and being the U.S. state with the highest volume of green bonds and a distinct tax system and market design make it a reflective laboratory of green municipal bond markets (Chiang, 2023). We find that Californian green municipal bond yields on average are positive in the early years but become negative after 2022.

We also develop a screening process that identifies relevant structuring attributes of positive and negative green bond yield spreads. This screening process can guide investors in the construction of optimal green bond portfolios tailored to their specific investment strategies and risk-return preferences (Lombardi Netto et al., 2021). From an issuer's perspective, green bond screening offers crucial insights into the financial setting of sustainable finance and helps them to strategically position their offerings and re-evaluate their cost of capital (Zhang et al., 2021). In addition to optimizing cost, green bonds allow issuers to enhance their reputation and attract a wider base of socially responsible investors. However, in the absence of clear and established screening methodologies, the selection criteria remain an open question. To inform municipal green bond screening criteria, we employ a machine learning technique, namely Association rule learning (ARL), to identify structuring attributes associated with positive and negative green bond yield spreads, including extreme

[3]Policymakers, including regulatory authorities, government agencies, international organizations, central banks, legislative bodies, and environmental agencies, play a crucial role in the green bond market by setting standards, providing market incentives, mitigating risks, and encouraging transparency. They create and enforce regulations that ensure that the proceeds from green bonds are used for genuinely sustainable projects, thus making these bonds more attractive to investors.

positive and negative spreads, and the consistency of green bond spread attributes over time. For a more comprehensive assessment, we also investigate higher-order and nested rules that consider combinations of attribute associations.

We find that classical attributes such as tax status, pricing strategy, and callability are important. More specifically, federal taxable, at-par, callable, and long-maturity green bonds are associated with positive spreads, while negative spreads are the result of more complex attribute interactions. Negative yield spreads are related to bonds with low spreads-at-issuance, and non-callable, tax-exempt, at-premium, and short-maturity bonds. Extreme positive spreads are associated to federal taxable and at-par bonds, with extreme negative spreads related to low spreads-at-issuance and short maturities. The temporal analysis confirms that tax status and pricing strategy remain strong attributes of positive spread, yet there is a fundamental restructuring on the municipal green bond attributes after 2022. Although after 2022 the associations for positive spread attributes strengthen substantially, the associations for negative spread attributes deteriorate. As green bond spreads are on average negative after 2022, this weakening of the rules implies that the high demand for green bonds drives the negative green bond spread irrespective of their structuring properties. Higher-order-rules identify combinations of attributes for positive and negative rules. Federal taxable, at-par, and revenue bonds have positive spreads, while combinations of non-callable, tax-exempt, at-premium, short-maturity, high-coupon with low spread-at-issuance bonds display negative spreads. The low spread-at-issuance feature of green bonds indicates a strong demand for green bonds reflected in the secondary market.

Motivated by these demand interactions, we demonstrate the economic significance of a screening process for structuring attributes in green municipal bonds from a market demand perspective. We evaluate the effects of subscription dynamics on attribute-defined segments identified by the proposed screening process. We gauge the effect of auction demand in major domestic and international markets (e.g. Japan) and macro-financial conditions shape green bond issuance of bonds with positive and negative yield spreads. We find that Japanese Treasury auction demand significantly transmits into U.S. green municipal bond pricing. Strong demand for Japanese Government bonds raises issuance yields in attribute-defined groups with positive spreads, which is consistent with a portfolio rebalancing channel. For negative yield spread groups, the effects are weaker but become significant in higher-order rules, indicating that demand shocks matter most in structurally homogeneous segments of green bonds.

We make three key contributions to research dedicated to green bond markets. First, we propose novel "green bond-specific" yield spread measures based on YTM to address the limitations of the literature. Existing studies focusing on the spreads (or premium) of green bonds use the classical notion of matching design to identify conventional bonds with characteristics similar to the green bond to construct the spread (Bhanot et al., 2022; Chang et al., 2024; Larcker and Watts, 2020; Partridge and Medda, 2020; Kapraun et al., 2021; Bour, 2019; Hachenberg and Schiereck, 2018; Zerbib, 2019). Relying solely on market prices, particularly for over-the-counter (OTC) instruments with limited trading activity, may not provide representative data for spread calculations. The decentralized nature of OTC markets often leads to illiquidity, where infrequent trading results in sparse price data, further complicating accurate spread assessment (Dorfleitner et al., 2023). The challenge of matching highly liquid bonds with less liquid ones also questions the validity of comparing them solely on price levels (Febi et al., 2018). To calculate the green bond yield spread, we compare each bond with a synthetic reference bond that reflects the structural specifications of the green bond, rather than comparing the green bond curve to a general reference curve.

Secondly, we propose a screening method for green bond attribute associations and conduct a comprehensive analysis of such associations in the municipal green market in California. This analysis delves into structuring attributes such as tax status, pricing mechanisms, and maturity. Although such attributes are considered critical determinants of the dynamics of the green bond market, the existing literature does not identify the complexities and temporal effects of positive and negative yield attribute structures in green bond markets. Note that positive yield spreads can reflect low liquidity and high credit risk in certain projects (Karpf and Mandel, 2018) and negative spreads can reflect high demand for sustainable investments, tax incentives, or scarcity of issuance (Flammer, 2021; Fatica et al., 2021). However, there is no clear understanding of the combinations of structuring attribute associations of bonds with positive and negative spreads, which is the void this work fills.

Third, we conduct an empirical investigation of demand transmissions in green bond markets by leveraging attribute-defined segments identified by the proposed screening process. We find that bonds with positive spreads are more responsive to Japanese Treasury actions compared to negative spreads, while higher-order rules become critical in identifying bonds that are sensitive to international demand shocks. We show that oversubscribed negative-spread bonds with specific attributed-defined structures are also vulnerable to such external shocks. These insights highlight the broader economic significance of our screening process that links municipal green bond attributes with global investor demand in shaping green bond yields, and contributes to the limited literature on cross-market demand transmission mechanisms in green bond markets (Hattori and Takahashi, 2021).

The divergent association trajectories between positive and negative spread, and their differential response to issuance demand have direct implications for investors and issuers in the green municipal bond market. This shift reflects evolving perceptions of green credit risk, which, unlike traditional credit risk, is influenced by the complexity of funded projects and their alignment with green labels and indices (Karpf and Mandel (2018)). From an investor's perspective, there is a need for a strategic shift to balance risk and return while supporting sustainability goals. Tax status and pricing strategies present potential opportunities, but tax implications must be carefully considered. Green bonds also offer diversification benefits that extend beyond traditional approaches (such as sector diversification), as they align with broader environmental goals. For issuers, the results emphasize the importance of structuring green bond offerings to attract investors, design bonds with favourable attributes that secure more competitive pricing, and help with diversification of their debt portfolios (Zerbib, 2019).

The remainder of the paper is organized as follows. Section 2 summarised the literature, and Section 3 explains the municipal green bond data, the computation of green bond yield spreads, and the ARL methods used for identifying associations. The attribute associations of the positive and negative green bond yield spreads and their interpretations are presented in Section 4. Section 5 demonstrates the economic importance of attribute associations in demand interactions in green bond markets. Section 6 concludes and discusses financial implications.

2. Literature Review

This study merges contributions from three strands of literature; measurement of green bond yield spreads, screening of structuring attribute associations, and transmission channels of demand.

2.1. The greenium debate

The measurement of green bond yield spreads has evolved substantially since the emergence of the "greenium", the premium investors pay for environmentally labelled securities, yet methodological limitations continue to constrain empirical analysis.

Early studies predominantly employed bond-matching designs, comparing green bonds to conventional counterparts with similar characteristics to isolate the environmental premium. Zerbib (2019) established the foundational approach by matching corporate green and conventional bonds across maturity, coupon rate, credit rating, and liquidity characteristics, finding a modest but significant negative premium of approximately 2 basis points. However, this matching methodology faces inherent limitations in illiquid markets where suitable conventional counterparts may not exist. Febi et al. (2018) show that liquidity risk significantly affects green bond yield spreads, with illiquid bonds exhibiting wider spreads due to trading frictions rather than fundamental credit or environmental factors. Similarly, Bhanot et al. (2022) demonstrate that liquidity constraints in municipal bond markets severely limit the applicability of bond-matching designs, particularly for green municipal bonds where trading volumes are often insufficient for reliable price discovery. These findings highlight critical shortcomings in traditional spread calculation methods and underscore the need for alternative methodologies that do not rely solely on market prices for spread calculation.

The limitations of price-based approaches have led researchers to explore yield-to-maturity (YTM) based methodologies. Unlike price-based measures that can be distorted by thin trading and market microstructure effects, YTM-based approaches leverage quoted yields that incorporate forward-looking return expectations. This methodological shift addresses the fundamental challenge identified by Dorfleitner et al. (2023), who demonstrate that green bond liquidity premiums can obscure true environmental pricing effects when relying solely on transaction prices. Recent research by Huang et al. (2023) proposes a quadratic function specification for greenium measurement, suggesting that traditional linear models may underestimate the complexity of green bond pricing relationships. We add to this strand of research by proposing a novel approach of non-parametric green bond spreads based on YTM that compares every green bond with a synthetic reference bond of matching tenor.

The temporal dimension of green bond pricing has revealed additional complexities. Karpf and Mandel (2018) document a structural shift in U.S. municipal green bond pricing, with initially positive spreads (reflecting investor unfamiliarity and credit concerns) transitioning to negative territories as market maturity increased. This evolution suggests that static spread measures may not adequately capture the dynamic nature of green bond markets. More recent contributions emphasize the dynamic and market-dependent nature of the greenium. Arat et al. (2023) show that the greenium widened during the COVID-19 pandemic, suggesting that green bonds outperform conventional ones under stress, though its magnitude varies with issuers' environmental performance. Recent large-scale studies provide stronger evidence of a greenium. Caramichael and Rapp (2024) find a 1–2 basis point issuance premium, concentrated among large, investment-grade issuers in the banking sector and developed markets. This finding aligns with Löffler et al. (2021), who document a consistent 15–20 basis point greenium in both primary and secondary markets. Sojoudi et al. (2025) apply a Nelson-Siegel yield curve framework to U.S. municipal bonds, generating time-series estimates that reveal the greenium to be highly variable across both time and maturities. Thus, we can conclude that the greenium is neither uniform nor static, but is shaped by methodology, market conditions, and issuer context. Our approach allows for a comprehensive temporal analysis which provides empirical evidence of a restructuring of the Californian municipal market after 2022, in terms of the attribute associations of positive and negative spreads reflecting their high demand.

The empirical evidence on the existence of a greenium remains mixed and varies across markets. Several studies focusing on corporate and international bond markets document a significant issuance premium for green bonds (Berdiev, 2025; De Vincentiis and Abis, 2025; Dragotto et al., 2025; Kapraun et al., 2021; Zerbib, 2019). In contrast, other studies find little or no evidence of such a premium, suggesting that the greenium is not uniform and may depend on issuer type, market conditions, or methodological choices (Flammer, 2021). Evidence from municipal markets provides a somewhat similar picture: research on U.S. municipal bonds indicates that a greenium can emerge, often linked to strong investor demand and structural features of the market, though results remain heterogeneous and context-specific (Chang et al., 2024; Bhanot et al., 2022; Partridge and Medda, 2018). At the same time, some studies report no apparent evidence of a greenium in municipal bonds (Larcker and Watts, 2020). The excessive focus on the greenium itself, along with differences in methodological choices, are among the main reasons for the mismatch in results across the literature. Green bond yield spreads, similar to those proposed in this study, are broader measures that capture the effects of a wide range of factors such as market conditions (Adekoya et al., 2023), tax incentives (Papavassiliou et al., 2025), market sentiment (Caramichael and Rapp, 2024), as well as non-pecuniary incentives, for example, environmental and reputational benefits (Bhanot et al., 2022; Zerbib, 2019; Flammer, 2021).

2.2. Determinants of bond spreads and screening methodologies

The identification and analysis of green bond attributes has emerged as a critical research area, driven by the recognition that environmental benefits interact with traditional bond characteristics in complex ways. With a focus primarily on credit-related attributes, Partridge and Medda (2020) examines how credit ratings, callability, and maturity structures affect green municipal bond pricing.[4] They find that traditional credit factors remain important determinants of green bond yields, but environmental characteristics create additional pricing dimensions that require specialized analytical frameworks. Tax status has emerged as another important attribute in green municipal bond analysis. Baker et al. (2022) provide comprehensive evidence that tax-exempt status significantly affects green bond pricing, with tax-exempt bonds exhibiting different yield patterns compared to taxable counterparts. This finding reflects the dual nature of investor demand, where tax-advantaged investors (such as high-net-worth individuals) and tax-neutral investors (such as pension funds) exhibit different sensitivities to environmental benefits. The interaction between tax status and environmental characteristics creates segmented markets with distinct pricing dynam-

[4]Credit ratings are more central to corporate bonds, where higher default risk makes them a key pricing factor, whereas municipal bonds are typically backed by state and local governments and exhibit very low default rates, reducing the reliance on ratings (Wang, 2022).

ics. Callability provisions represent another critical dimension identified in recent research. Fatica and Panzica (2021) demonstrate that callable green bonds trade at different premiums compared to non-callable issues, reflecting the embedded option value and its interaction with environmental demand. Financial institutions exhibit particular sensitivity to callability features when investing in green bonds, suggesting that institutional demand patterns vary across bond structures. This analysis reveals that despite the green bond market's small size relative to conventional bonds, the greenium persists across different institutional investor types, with varying magnitudes based on callability features. Maturity effects in green bonds exhibit unique characteristics compared to conventional bonds. Flammer (2021) shows that long-maturity green bonds may command premiums due to their alignment with long-term sustainability goals, while short-maturity issues appeal to investors seeking liquidity without sacrificing environmental objectives. This maturity segmentation creates distinct yield curve dynamics that require specialized analytical approaches. Li et al. (2022) further document how maturity interacts with other bond characteristics in the Chinese green bond market, revealing complex interaction effects that vary across market conditions. The role of certification and third-party verification has gained increased attention in recent literature. Studies by Tan et al. (2022) and Wang et al. (2020) demonstrate that certified green bonds exhibit different pricing patterns compared to self-labeled bonds, with certification providing additional credibility that translates into tighter spreads. Thus, governance mechanisms are critical in green bond markets and an attribute analysis must account for quality differentials beyond basic structural characteristics.

Although regression and yield-curve-based methods help identify average pricing effects of individual attributes, they often fail to capture combinatorial interactions that jointly shape spreads. The application of machine learning techniques to bond attribute analysis represents a significant methodological advancement. Gaining higher attention in financial applications (Dai et al., 2024; Srivastava et al., 2024), ARL provides a complementary, nonparametric approach by uncovering recurring high-order attribute bundles such as tax status, callability, maturity, and issuer type that systematically align with narrower or wider spreads. In markets where the trading data are thin, ARL can instead be applied to the issuance characteristics and allocation patterns, revealing hidden investor demand structures.

To the best of our knowledge, this study is the first study surfacing these attribute combinations in green municipal bond markets, transforming scattered micro-signals into actionable design rules, and offering issuers practical guidance for structuring green bond offerings that can attract demand and reduce funding costs.

2.3. Effects of demand transmission and international capital flows

The analysis of demand transmission mechanisms in green bond markets has become increasingly important as these instruments attract global investor attention. Cross-border capital flows and international investor behavior create spillover effects that can significantly influence domestic green bond pricing, yet research in this area remains limited compared to conventional fixed-income markets. Studies examine spillover effects between green bonds and other financial markets, e.g. linkages with equity markets (Wang et al., 2025, 2024; Gao et al., 2023; Ejaz et al., 2022; Kocaarslan, 2021; Pham, 2021), energy and commodity markets (Su et al., 2023; Rehman et al., 2023; Naeem et al., 2021), cryptocurrencies (Rizvi et al., 2022), and broader financial connectedness (García et al., 2023; Khamis and Aassouli, 2023; Tiwari et al., 2023; Naeem et al., 2022; Nguyen et al., 2021).

Chen et al. (2024) show strong volatility spillovers between Chinese green and conventional markets, while Gyamerah and Asare (2024) review 79 studies and conclude that green bonds act as net transmitters of spillovers in the short run but shift to net receivers in the long run. Yousaf et al. (2024) report weak oil–green bond connectedness, highlighting hedging potential, and Mertzanis and Tebourbi (2025) together with Fiorillo et al. (2024) demonstrate how geopolitical risk shifts investor preferences toward or away from green bonds during periods of turmoil. Collectively, these studies establish that green bonds are embedded in global risk transmission networks. Additionally, currency and hedging considerations add complexity to cross-border green bond demand. For foreign investors in dollar-denominated municipals, hedging costs and currency volatility that often are shaped by central bank policy divergence can drive shifts in demand independent of credit fundamentals. Moro and Zaghini (2025) show that exchange rate volatility and financial openness systematically influence green premia, with impact varying according to the degree of market integration.

Beyond spillovers, a smaller but growing literature has focused on demand transmission mechanisms. Sovereign bond auctions provide a useful framework: Hattori and Takahashi

(2021) show that Japanese Government Bond bid-to-cover ratios signal broader investor risk appetite, with implications for cross-market transmission. This perspective is particularly relevant for U.S. municipal markets, where international investors, especially Japanese insurance companies and pension funds facing persistently low domestic yields, have become major buyers of taxable municipals. Shifts in Japanese auction demand and domestic yield conditions can therefore propagate into U.S. fixed income through portfolio rebalancing and liquidity channels, directly shaping municipal bond pricing. Adekoya et al. (2023) further suggests that global investor sentiment and risk appetite amplify these demand spillovers, as the ESG investor base tends to be internationally diversified and sensitive to macro-financial conditions. We demonstrate that demand for Japanese Treasury auctions systematically increases issuance yields for Californian municipal green bonds, a demand-induced effect that is typically evident in more structurally defined segments of green bonds, as identified by our machine learning technique (ARL).

3. Data, Yield Spread Calculation and the ARL Method

This section begins with the data description. We next describe the calculation of novel green bond yield spreads and the machine learning approach used to identify their attributes associations. The statistical properties of the synthetic municipal green bond yield spreads in California are also presented.

3.1. Data Description

We collect daily YTM data for the U.S. municipal green bonds from the Bloomberg Information Services terminal. Bonds are classified as "green municipal bonds" using Bloomberg's indicator function. Each bond, distinguished by a unique CUSIP number, serves as our observation unit. Furthermore, we gather 34 structuring attributes related to both the bonds and their issuers, as described in Appendix A, based on the CUSIP number. This CUSIP is used to match the yield datasets with the attributes datasets.

Our dataset consists of the yields of municipal green bonds issued in California between 2016 and 2024.[5] California serves as a representative case for this study, as it represents the

[5] To remove potential outliers in the yield variable, we employ a two-step iterative process based on Z-scores, which is detailed in Appendix B.

largest green municipal bond market in the U.S. with established leadership in environmental policy (California Green Bond Market Development Committee, 2023). Thus, it offers a wide range of green bonds with diverse structuring properties and attributes. Furthermore, California has a stable taxation framework, a broad range of issuers, industries, and green projects (UOPs), and represents a significant issuance volume.

Different types of U.S. Treasury yield curves can be used to derive discount factors and serve as benchmarks for spread comparison.[6] In the context of a time series measured in monetary values, inflation is often a major driver and significant contributor to volatility (Cecchetti et al., 2007). In our analysis, where we specifically focus on nominal bond yields without adjusting for inflation, we choose par yields, rather than the real par yields of U.S. Treasury bonds. The par yield of a security is related to the time until it matures, and its calculation uses the closing market bid prices of recently auctioned Treasury securities in the OTC market. The par yields are calculated from market prices, estimated quotes obtained by the Federal Reserve Bank of New York. Unlike the inflation-adjusted or real par yield curve, which incorporates inflation expectations, using par yields allows us to compare nominal yields without the additional adjustment directly. Both par and real par yield rates datasets are available from the U.S. Department of the Treasury.[7] A plot with the U.S. par yield data series is presented in Appendix C.

3.2. Green bonds yield spreads based on YTM

We propose a novel approach to compute green bond yield spread based on YTM, in which the spread is computed as a non-parametric spread based on a tenor-specific approach calculated for each individual green bond across the dataset on a daily basis.

We follow a three-step process. First, we calculate the value of a specific green bond synthetically, using the market-quoted $YTM^{(G)}$ of this green bond to discount its cash flows. Thus, all the cash flows of a specific green bond are discounted by the same fixed rate, which is its YTM. The synthetic[8] value of this specific bond is then used to compute the

[6] Other reference risk-free U.S. rates, such as standard yield, inflation-adjusted yield, or real par yield, may also be utilized depending on the context.

[7] U.S. Treasury Interest Rate Statistics

[8] We call these rates synthetic because they are not traded in the market.

equivalent green zero-coupon bond YTM. Accordingly, at time t and for each green bond i with face value of FV,[9] coupon payments C_i, and annualized quoted $YTM^G_{i,t}$, which has payments in N periods from first issuance, $\mathbb{I}(\cdot)$ an indicator function to identify the timing of coupon payments, and $\tau_{i,n}$ be the remaining year fraction to the n^{th} payment, the green equivalent Zero-Coupon Bond Yields to Maturity, denoted as $YTM^{(GZCB)}_{i,t}$, is computed as:

$$YTM^{(GZCB)}_{i,t} = \left[\frac{1}{\widetilde{FV}_i}\left(\sum_{n=1}^{N}\frac{C_i\mathbb{I}(\tau_{i,n})}{(1+YTM^{(G)}_{i,t})^{\tau_{i,n}}} + \frac{FV_i}{(1+YTM^{(G)}_{i,t})^{\tau_{i,N}}}\right)\right]^{-\frac{1}{\tau_{i,N}}} - 1. \tag{1}$$

Second, the corresponding reference rate from a risk-free yield curve is selected, so it matches the tenor of this specific green bond. We then use this reference rate as the fixed rate to discount the same cash flows to compute a synthetic reference bond price and used it to determine the equivalent risk-free zero-coupon bond YTM. Thus, the reference equivalent Zero-Coupon Bond Yields to Maturity, $YTM^{(RZCB)}_{i,t}$ is computed as:

$$YTM^{(RZCB)}_{i,t} = \left[\frac{1}{\widetilde{FV}_i}\left(\sum_{n=1}^{N}\frac{C_i\mathbb{I}(\tau_{i,n})}{(1+r^{(Tr)}_t(\tau_{i,N}))^{\tau_{i,n}}} + \frac{FV_i}{(1+r^{(Tr)}_t(\tau_{i,N}))^{\tau_{i,N}}}\right)\right]^{-\frac{1}{\tau_{i,N}}} - 1, \tag{2}$$

where $r^{(Tr)}_t(\tau_{i,N})$ is the corresponding reference rate for $\tau_{i,N}$ year(s) maturity bond at time t. Note that the discount factors $r^{(Tr)}_t(\tau_{i,N})$ are derived from the fitted spline curves of annual reference rates at time t, based on the same tenor as the green bond. Lastly, the difference between the green and the risk-free zero-coupon bond YTM determines the spread of this specific green bond, namely,

$$S_{i,t} := YTM^{(GZCB)}_{i,t} - YTM^{(RZCB)}_{i,t}. \tag{3}$$

This tenor-specific approach uses a single matching tenor point on the green and reference yield curves and compares a time series of a green zero-coupon bond YTMs with a time series of risk-free zero-coupon bond YTMs at the same tenor point to obtain the spread of this specific green bond. This method is repeated for all green bonds on a certain day, and consequently yield spreads for all available green bonds on this day are computed. The full technical details of the green bond yield spread computations are presented in Appendix D.

[9] $\widetilde{FV}$ It is adjusted for bonds that pay both the final coupon and the principal at maturity. This adjustment is crucial because, when the last coupon coincides with maturity, it ensures the equivalent zero-coupon bond accurately reflects the bond's full cash flow structure.

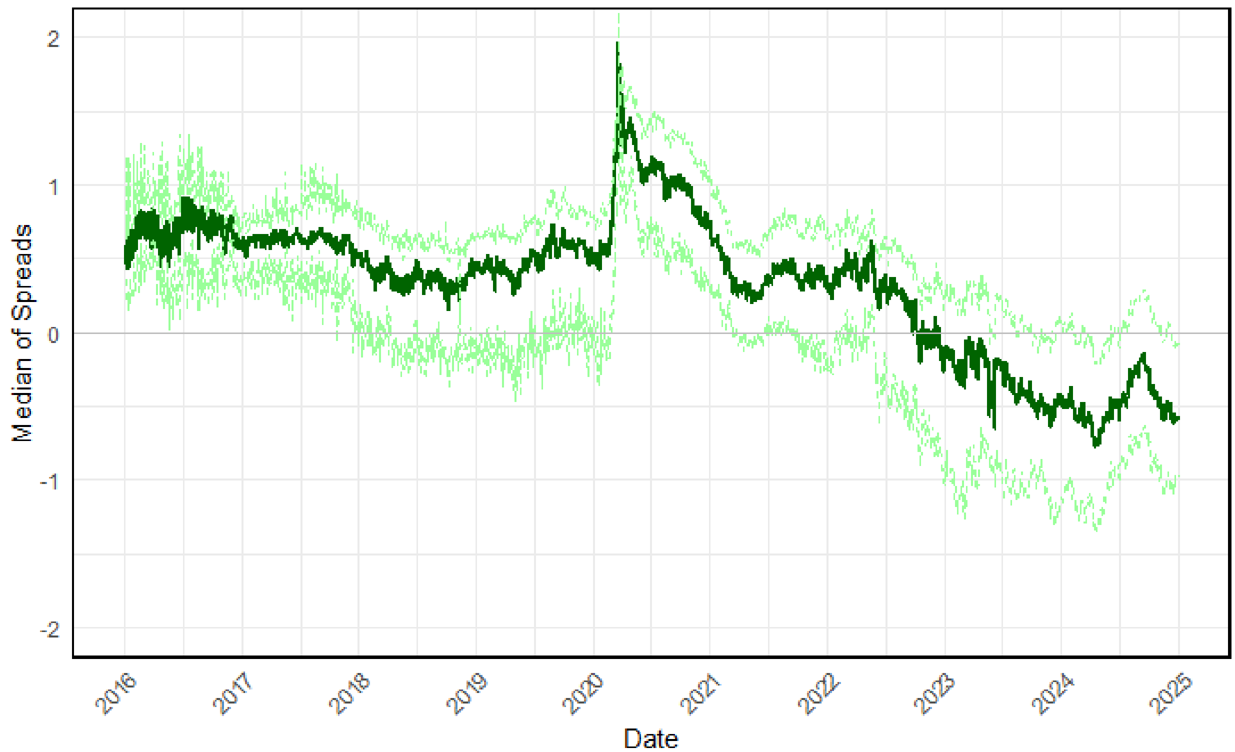
The innovation of the proposed green bond yield spread lies in the evaluation of green bond yield spreads based on the YTM. This evaluation approach addresses critical limitations of the green bond literature, especially in the context of illiquidity and OTC pricing complexities between green and conventional bond markets (Dorfleitner et al., 2023). Using YTM for the evaluation of (green and conventional) bond prices facilitates direct comparisons across a range of bonds, irrespective of their price, maturity, or coupon rate.[10] Based on the Bloomberg's Yield and Spread Analysis instructions, they offer a standardized framework for calculating bond yields. Bloomberg's advanced algorithms account for key factors such as market data, interest rates, and issuer credit quality. Thus, this approach helps mitigate potential inaccuracies in market prices often seen in illiquid and OTC bond markets, while ensuring that the computed prices and yield spreads are aligned with industry standards. Furthermore, using zero-coupon bond equivalents facilitate enhanced comparability to reference curves, which are typically in zero-coupon bond forms, ensuring accurate assessment of green bond performance and yields relative to other bonds. The proposed conversion facilitates like-for-like comparisons on a per bond basis and offers an adaptive perspective on the bond's value based on prevailing market conditions and expectations.

3.2.1. Green municipal bond yield spreads in California

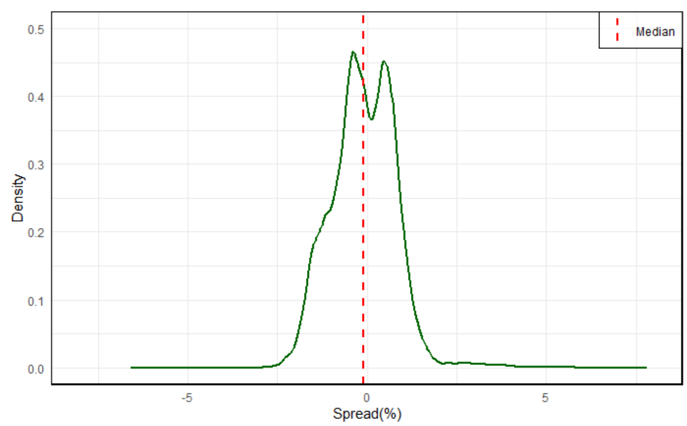
Based on the approach described in Section 3.2, Figure 1 shows the median of the daily green bond yield spreads in California and their kernel density between 2016 and 2024. To compute the equivalent zero-coupon reference rate that matches the tenor of the individual green bond, we extract the corresponding rates from the U.S. Treasury curve on the corresponding day.[11] Table 1 presents a statistical summary of the green bond yield spreads.

[10] YTM incorporates the comprehensive return of the bond, accounting for interest payments and the impact of purchasing at a discount or premium to par.

[11] To extract the corresponding rates from the U.S. Treasury curve, we employ daily cubic Basis Spline (B-Spline) regression interpolation of the U.S. Treasury par yield rates in a bootstrapping procedure over a term structure range up to thirty years. Appendix E discusses the benefits of B-spline curves and presents demonstrative examples of the fit of the B-spline curves in the U.S. Treasury curve. A third-degree curve is selected for regression estimation (B3-spline) to enhance the accuracy of interpolation rate, thus three knot points are derived from the interquartile range and median.



(a) Median of daily green bond yield spreads



(b) Kernel density of green bond yield spreads

Figure 1: **Green bond yield spreads based on YTM in California (2016-2024)**
The top panel displays the daily median of the green bond yield spreads in California. The green dashed lines represent the 25th and 75th percentiles of the spreads. The bottom panel shows the kernel density estimate of the spread, with the red dashed line indicating the sample median.

We observe that the medians of the spreads are positive in the first periods and reach negative territories after 2022 with higher standard deviations. The noticeable downward trend in green bond yield spreads in recent years may be driven by an increase in the demand for green bonds due to a change in the preferences of ethically motivated investors to meet sustainability goals. This demand is driven by institutional investors like pension funds, which seek to hedge against long-term risks such as climate change while meeting regulatory and beneficiary demand for ESG-aligned investments. Similarly, insurance companies use green bonds to match liabilities, aligning their long-term liabilities with sustainable assets that mitigate climate-related risks. Recent studies highlight the emergence of a premium in the U.S. municipal bond market driven by growing investor preferences for sustainable investments (Karpf and Mandel, 2018). The kernel density also displays a dual feature that exhibits one positive and one negative peak, highlighting the distinct importance of positive and negative spreads.

3.3. Identify attributes of the green bond yield spreads via ARL

The study of associations between attributes of green bonds and their yield spread behaviors over time can be framed as an exercise in ARL, see Agrawal et al. (1993). ARL is a data mining technique that aims to uncover relationships, patterns, or associations among items in large datasets. However, it is important to note that ARL does not identify or imply causal relationships, as its purpose is detecting statistical associations rather than establishing cause-and-effect mechanisms. This method is widely used in market basket analysis, customer segmentation, and recommendation systems (Srivastava et al., 2024; Yang and Wu, 2025; Huang et al., 2023). ARL is traditionally used to identify frequent itemsets, i.e. groups of items that co-occur frequently in transactions, and derives rules that describe their co-occurrence in terms of support, confidence, and lift. Support shows how often a set of items appears in the whole dataset. Confidence shows how often the second item appears when the first one is present, so it reflects the conditional probability of an itemset. Lift compares this relationship to what would happen if the two items were unrelated: a value above one means they occur together more than expected, a value around one means there is no real link, and a value below one means they occur together less than expected.[12]

Traditionally, the learning of Association Rules (AR) in an ARL framework has to use

[12]For any itemsets A and B, the support, confidence, and lift of the association $A \Rightarrow B$ are defined respectively as: $\text{Support}(A \Rightarrow B) = \frac{|A \cap B|}{N}$, $\text{Confidence}(A \Rightarrow B) = \frac{|A \cap B|}{|A|}$, $\text{Lift}(A \Rightarrow B) = \frac{|A \cap B|}{|A| \cdot |B|}$, where N denotes the total number of transactions (observations) and $|\cdot|$ represents the cardinality of the corresponding set.

an algorithmic search method. The Apriori algorithm is one of the most popular and foundational methods for ARL. It uses a bottom-up, breadth-first search approach to generate frequent itemsets, exploiting the property that any subset of a frequent itemset must also be frequent. Apriori operates in two phases: first, it identifies all frequent itemsets based on a minimum support threshold, and second, it generates association rules from these itemsets using a minimum confidence threshold.[13] The choice of thresholds was validated for robustness by testing alternative confidence quantile settings for the generated rules. Higher quantile values substantially reduced the number of retained rules, limiting coverage but leaving the top-ranked associations qualitatively unchanged. This confirms that the thresholds adopted in this paper yield robust and representative patterns while preserving analytical comprehensiveness and computational efficiency. A detailed explanation of the methodological aspects of the ARL framework and the Apriori algorithm is presented in Appendix F.

In this study, we formulate an ARL solution in a time series context and seek associations of green bond structuring attributes, such as tax status, coupon rates, maturity, and credit rating, within green bonds dynamic spread over monthly sliding windows of time, after their initial issuance. A screening process of practical relevance would be to identify structuring attributes associated with positive and negative green bond spreads. Positive yield spreads, where green bonds offer higher yields than a comparable benchmark, can arise due to factors such as market unfamiliarity, low liquidity concerns, and high credit risk in certain projects (Karpf and Mandel, 2018). In contrast, negative spreads can reflect high demand for sustainable investments, tax incentives, regulatory benefits, or strong creditworthiness and scarcity of issuance (Flammer, 2021; Fatica et al., 2021). Issuers may also offer lower yields to enhance their reputation and attract a broader investor base. Furthermore, municipal green bonds are typically tax-exempt, making them particularly attractive to investors and allowing issuers to provide lower yields. Local investors may also accept reduced returns to support environmentally beneficial projects within their communities (U.S. Environmental

[13] While, the algorithm is efficient for smaller datasets, its performance can degrade with larger datasets due to the exponential growth in the number of candidate itemsets. Optimizations and alternative algorithms, such as FP-Growth, have been developed to address these challenges.

Protection Agency, 2024).

Motivated by these insights and with the aim of providing a comprehensive screening assessment, we next use the ARL approach to: a) identify the key attribute associations for positive and negative green bond yield spreads, b) find attribute associations for extreme values of yield spreads, c) assess the temporal consistency of these rules, and d) evaluate nested associations of green bond attributes (higher-order rules). To apply ARL for identification of attribute associations and their temporal effects, we first perform several preparation steps involving a labelling process, parameter setting and the selection of the model order, which are detailed in Appendix G. In this paper, this screening method is applied in the Californian green municipal market, but it can be easily extended to other state municipal bond markets, developing green bond markets, and corporate green bond markets.

4. Attributes associations of green bonds spreads

In this section, we report the results of a comprehensive screening assessment of the attribute associations of the green bond yield spreads in California.

4.1. First-order attributes of positive and negative green bond spreads

We start with identifying the attribute associations of positive and negative spreads by using one state of attributes to generate association rules, which we denote as "first-order" rules.[14] Table 2 presents the support, confidence, and lift of the such associations rules for positive and negative green bond yields spreads as ranked by confidence. The first-order attribute associations of the positive and negative spreads based on confidence and support are also depicted in Figure 2. The circle size indicates the confidence, and the color intensity represents the support (its frequency).

From Table 2 and Figure 2, we conclude that the top-ranked association (based on confidence) for positive green bond yield spreads is the federally taxable bonds with confidence 1 and support 0.18. Thus, all federally taxable bonds (100%) are associated with positive spreads and comprise 18% of the sample size of green municipal bonds in California.

[14] The order of a rule denotes the number of variables or attribute states on the left-hand side (LHS) of the association. As we set the right-hand side (RHS) of the rules as positive and negative spreads, an "order 1" rule represents the case where a single itemset is considered in the RHS. Note that, in the arules package, rule order refers to the number of item sets in the entire rule, thus denotes this as a second-order rule.

A strong lift for this rule (at 1.85) also confirms the reliability of this association.[15] The second-ranked association is the bonds issued at par, where 98% of them are associated with positive spreads and consist 16% of the sample size. Positive spread associations are also related to bonds with long durations and high yields on issue date, as well as to callable bonds (65% of callable bonds which make up 42% of the green bonds in California).

While confidence and support are statistical metrics describing the strength and prevalence of associations, their economic relevance can also be interpreted qualitatively. For instance, federally taxable green bonds identified with full confidence as associated with positive yield spreads, typically entail higher borrowing costs than tax-exempt issues, reflecting the absence of tax advantages and the higher yields demanded by investors. Positive spreads for taxable bonds, particularly for long-maturity bonds, typically reflect that investors in lower tax brackets or tax-advantaged accounts (e.g., pension funds) prioritize pre-tax yields over tax savings, especially in high interest rate environments.[16] Further, bonds issued at par often exhibit positive spreads, reflecting favorable pricing relative to risk-free benchmarks. Callable bonds, which allow issuers to redeem bonds before maturity, are typically associated with positive spreads due to the embedded option risk and insurance provision (Baker et al. (2022)).

The top-ranked association for negative spreads is bonds with spread on issue date (S_OID) being less than 17. This association has a confidence of 0.83 and support 0.20, thus 83% of bonds with spread on issuance date to be less than 17 associated with negative spreads and consist 20% of the sample size of green bonds. The lift for this rule (1.85) also shows the reliability of this association. The association of negative spreads with bonds that have spreads on issue date less than 17 indicates that bonds already issued with lower spreads on the primary market continue to exhibit negative yield spreads on the secondary market. This pattern reflects strong demand at the time of issuance. The persistence of

[15] A lift of 1.85 means that the LHS attribute(s) (namely federal taxable) and the positive spreads occur together 1.85 times more frequently than would be expected if they were independent.

[16] In practical terms, even moderate spread differentials commonly observed for taxable municipal bonds can translate into substantial financing costs when scaled to large issuance volumes. Thus, the ARL-identified patterns are consistent with established pricing logic in municipal markets and have direct implications for issuer funding strategies, even though the underlying metrics are non-monetary.

these negative spreads in the secondary market, as confirmed by the strong rules, suggests that demand pressure remains high beyond the primary market stage (Partridge and Medda, 2018; Karpf and Mandel, 2018). In other words, the negative spread attributes leave a visible "demand footprint" in secondary pricing, a point we will investigate more directly in our analysis of spread behavior and demand dynamics in Section 5.

With relatively similar confidence (ranging from 71% to 56%) short duration bonds (18% of the sample), non-callable bonds (24%), bonds issued at premium (43%) and tax-exempt bonds (44%) are associated with negative yield spreads. The lift values for both positive and negative rules are consistently greater than one, further demonstrating the strength of these attribute associations (see Table 2). Bonds issued at a premium may be associated with negative spreads due to oversubscription and increased demand. Premium issuance, a phenomenon highlighted in Baker et al. (2022), reflects strong investor confidence in green bonds. Investors accept lower yields for sustainable investments as they prioritize environmental benefits over incremental yield advantages (greenium effect). Furthermore, oversubscription rates, highlighted in Environmental Finance (2023), provide additional evidence of the strong demand for green bonds, which contributes to the premium issuance pricing. Non-callable bonds may exhibit narrower spreads as they provide greater certainty to investors, enabling the mitigation of short-term risks (Baker et al. (2022)). Furthermore, tax-exempt bonds may display negative spreads, due to higher demand from high-net-worth investors seeking after-tax returns (Partridge and Medda (2020); Baker et al. (2022)).

We further identify attribute associations of extreme positive and negative green bond spreads. We consider the lower quantile of the green bond yield spreads as the *extreme negative* (S(extreme($-$))), and the upper quantile as the *extreme positive* (S(extreme($+$))).[17] Figure 3 shows the first-order attribute associations for extreme positive and negative spreads. The emerging attribute associations for extreme positive spreads (for different orders) are

[17]For generating rules for the extreme spreads, we designated the right-hand side ($LHS => RHS$) of the rules as S(extreme(+) or S(extreme($-$). Limited to 50% of observations for this analysis, we applied a min_supp of 0.01 and a min_conf similar to the previous step to identify rules associated with extreme positive (or extreme negative) spreads in the dataset. To enhance the extraction of meaningful and robust rules, and since we employ a relatively lower threshold for support, we introduce a new measure, which is the product of support and confidence ($supp\_conf$). This measure allows us to pinpoint rules with high support and confidence simultaneously.

taxable, at par, and while spread-at-issuance date less than 17 and maturity-related attributes for negative spreads.[18]

Thus, we conclude that tax status, pricing strategy, callability, spreads on issuance date, and duration-related attributes emerge as leading green bond attributes that have distinct effects on green bond yield spreads. In Appendix H, we also investigate the contribution of these attributes to the yield spread variations using ANOVA, and the results further confirm the validity of these associations.

4.2. Temporal consistency of the associations

Figure 4 compares the trends of the attribute associations of positive and negative yield spreads based on confidence, support, and lift. These trends are computed using monthly frequency of the spreads.

For positive spread attributes, Figure 4a shows that federal taxable bonds consistently exhibit the highest confidence levels (approaching 1.0) over the sample period, indicating that federal taxable bonds are consistently associated with positive yield spreads. At-par bonds exhibit similar resilience most of the time. The confidence levels for the other green bond attributes demonstrate declining associations over time, particularly after 2022. The decline is most severe for maturity-related attributes and callable bonds, where confidence levels fall from relatively stable positions around 0.8-0.9 in the early periods to 0.4-0.6 by 2024. Support for positive spread attributes shows a stable reduction across most characteristics as the overall spreads in the green bond market tend to decline in recent years, see Figure 4c. In terms of the lift, Figure 4e shows that tax status (federally taxable) and pricing strategy (at par) display a significant increasing trend, indicating that these attributes develop a strong association with positive spreads during the sample period.

Negative spread associations exhibit the opposite trajectory across the three metrics. Confidence demonstrates a consistent upward trend throughout the 10-year sample period (Figure 4a). Support shows increasing patterns, particularly for non-callable bonds and premium-issued bonds, suggesting that these characteristics are dominating green bonds with negative yield spread. The inflection point around 2022 represents a critical market

[18]Additionally, rules related to issuer markets (Special Tax, San Francisco City & County, and Special Assessment) can also be observed, though they appear only with relatively low confidence for positive spreads.

transition coinciding with the documented shift where, on average, spreads turned negative. Prior to 2022, lift values for positive and negative spread attributes showed a relatively stable trend, suggesting a more balanced market. The post-2022 period demonstrates a clear regime change where the lift values for negative spread attributes weaken substantially, indicating a weak association between structuring attributes and negative spread, see Figure 4c.

Our temporal analysis reveals a fundamental restructuring of the green municipal bond market characterized by divergent trajectories between positive and negative spread associations. The post-2022 period associations for positive spread attributes, such as tax and pricing strategy, strengthen substantially, while associations for negative spread attributes deteriorate. Considering that green bond spreads after 2022 are predominantly negative, this temporal pattern aligns with the growing investor demand for green bonds and indicates that environmental considerations have become dominant pricing factors, in such a way that excessive demand has led to negative green bond spread regardless of their different structuring properties. This evolution reflects a market transformation in which previous financial concerns and structural analysis have been supplemented by environmental and sustainability considerations, with the green municipal bond market reaching a maturity level in which environmental concerns have become primary rather than secondary pricing determinants. This shift necessitates a closer investigation of the role of investors demand in determining green bond spread dynamics, which is investigated in Section 5.

For a more comprehensive assessment that accounts for and integrates multiple attributes of green municipal bonds, we also study the nested effects of these associations by considering associations with higher number of itemsets.

4.3. Higher-order association rules

This section delves into higher-order association rules. We investigate higher-order rules to dig deeper into bond structuring attributes, revealing more nuanced demand patterns and investor risk attitudes that might remain hidden in first-order rules. Nested rules, based on the identified strong association rules from previous orders, are used to explore higher-order rules to the fullest extent possible. Table 3 presents the support, confidence, and lift of the top five higher-order rules (if they exist) for positive and negative green bond yields spreads ranked by confidence. Results for extreme positive/negative higher-order rules are also presented in parallel coordination in Appendix I.[19]

We find that federally taxable bonds combined with attributes such as at-par pricing, absence of a credit rating, self-reported green status, and revenue bonds are strongly associated with positive spreads. Indeed, 99.80% of such bonds are associated with positive yield spreads with a lift of 1.846. However, as the order of the rules increases, there is a noticeable decrease in the number of strong attribute associations for positive green bond yield spreads.

Higher-order rules for negative spreads are more complex and there is an increase in both support and confidence as we progress to higher-order rules. The second-order attribute associations of negative spreads, e.g. when two states of attributes are used to generate association rules, reveal that $88-89\%$ of these bonds have spread-at-issuance less than 17 and they are non-callable or have relatively short maturities.

The third- and fourth-order rules are very strong associations that have a confidence of $90-91\%$ and a lift of 1.99. Beyond being non-callable bonds with spread-at-issuance less than 17, new attribute associations emerge, such as money financing, coupons between $5-8.5\%$, tax-exempt, at premium and short maturity bonds. Supplementing the notion that non-callable bonds with spread-at-issuance less than 17 reflect high demand beyond the primary markets, premium issuance also provides evidence of strong demand for green bonds. The premium pricing has implications that vary with bond's maturity. For short-maturity green bonds, the premium roll-down effect may not have time to materialize, resulting in negative spreads. Issuers of longer-maturity green bonds may leverage excess demand to extract higher premiums, potentially related to negative spreads (see also Appendix I).

Further, the issuance of green bonds at par or premium often reflects market dynamics, including oversubscription and excess demand over supply at issuance. Premium issuance, a phenomenon highlighted in Baker et al. (2022), reflects strong investor confidence in green bonds. This "greenium" effect, where investors accept lower yields for sustainable investments as they prioritize environmental benefits over incremental yield advantages. Fur-

[19] Using Bayesian model selection (BMS), we identify the strongest rules for positive and negative spreads, highlighting the primary bond attributes that drive spread behavior (see Appendix G). As the rule order increases in the positive-spread regime, the number of strong rules declines, which aligns with the BMS results. In other words, the posterior probability of positive-spread models decreases with order, whereas the opposite holds for negative-spread models.

thermore, oversubscription rates, highlighted in Environmental Finance (2023), provide additional evidence of the strong demand for green bonds, which contributes to the premium issuance pricing. Note that tax-exempt green bonds may appear attractive to high-net-worth investors seeking after-tax returns. To attract high-net-worth investors, tax-exempt green bonds offer relatively high coupons to compensate for the lower pre-tax yields. Finally, non-callable bonds with shorter maturities/durations offer stability and narrower spreads (Partridge and Medda (2020)).

With callability and tax status of green bonds merging as strong structuring attributes, we also analyse attribute associations of positive and negative green bonds within a certain callability and tax status. Appendix J presents this analysis that provides similar conclusions regarding the nested association of positive and negative yield spreads. For example, we find that taxable green bonds in lower coupon ranges and tax-exempt bonds in higher coupon ranges and longer maturities are generally associated with positive spreads.[20] Tax-exempt bonds with longer maturities and higher coupon rates align with buy-and-hold investors optimizing after-tax returns. To attract high-net-worth investors, tax-exempt bonds offer higher coupons to compensate the lower pre-tax yields. In contrast, taxable bonds typically offer lower coupons to offset the reduced after-tax investors' returns. Also, taxable bonds with shorter maturities may appeal to institutions seeking liquidity rather than tax benefits Fatica et al. (2021); Karpf and Mandel (2018). For more targeted reflections on the potential environmental impact of the spreads, we also examine attribute associations of positive and negative green bonds within certain issuer sectors and UOPs, see Appendix J.

5. Economic significance of green bonds' screening: A demand perspective

Recent developments in global fixed-income markets manifest a sharp deterioration in the auction demand for Japanese Government Bond (JGB), with bid-to-cover ratios falling to historic lows. These conditions offer an exogenous shock to examine cross-border liquidity

[20] The importance of coupon rates emerges more prominently when controlling for tax status and callability, which often act as confounding variables (see Figures J.3 and J.4). This phenomenon occurs when two variables are marginally associated due to their mutual dependence on a third variable (the confounding variable). By conditioning on the confounding variable, the marginal association between the original two variables is removed, and their independent effects can be identified. Our analysis also shows that the tenor-specific spread is highly correlated with coupon rates.

signal effects on demand in the U.S. municipal green bond markets.[21] Japanese institutional investors have become significant participants in U.S. municipal bonds, thus changes in domestic JGB auction dynamics may systematically influence green municipal bond yields at issuance. How can such market demand shocks affect the performance of green bonds? How structurally homogeneous green bonds, based on a screening process identifying associations of positive or negative yield spreads, respond to international treasury market conditions or shocks?

We demonstrate the economic significance of the ARL-facilitated screening process through a green bond subscription analysis that gauges the impact of the demand for bond issuance on attribute-defined segments in green bond markets. This study examines a significant yet understudied channel of the cross-border financial transmission of variations in Japanese government bond (JGB) auction demand in the liquidity in U.S. municipal green bonds. Using grouped time series regressions, we quantify the impact of treasury auction dynamics on green municipal bond markets while leveraging the bond groupings identified through the ARL-facilitated screening process. This screening process can guide issuers on the timing of their offerings and investors on anticipated effects of macro-economic shocks on their bond portfolio performance. Moreover, framing Japanese auction metrics as exogenous demand shocks provides a fresh lens on the sovereign–municipal spillover effect, one that is especially relevant amid heightened uncertainty in global fixed income markets and growing attention to sustainable finance.

[21] In mid-2025, long-term JGB yields rose sharply, with 30-year yields climbing to approximately 3.1–3.2%, and 40-year yields reaching 3.385%, marking the highest levels in decades. At the same time, demand at these auctions weakened, with bid-to-cover ratios falling to historic lows—for instance, 2.127 for 40-year bonds (the weakest since 2011) and 2.921 for 30-year bonds, indicating pronounced market stress and diminished investor appetite. Analysts have linked this weakening demand to political uncertainty, demographic shifts, and reduced Bank of Japan support, warning that these developments may exert downward pressure on global bond demand and yield curves (The Wall Street Journal, 2025; Financial Times, 2025; The Economic Times, 2025). At the same time, U.S. taxable municipal bonds continue to attract foreign institutional investors, especially from Japan and Europe, as they offer yield premiums that are otherwise unavailable in low- or negative-rate domestic markets. Foreign holdings, particularly in taxable muni bonds, have grown as investors chase stable returns and diversification opportunities despite lacking tax advantages (Bredeson, 2024; Climate Bonds Initiative, 2024).

5.1. Model specifications

To specify the grouped time-series regressions, the green bonds are grouped based on the ARL rules for positive and negative green bond yield spreads with the highest confidence at each order (first up to the three), see Tables 2 and 3 for rules details. Selecting the strongest rule with the highest confidence per order avoids redundancy and targets the strongest bond groups with positive and negative associations.[22] For each group g, the dependent variable is the yield on issue date t, denoted $y_{g,t}$.[23] We consider the median of the yield on issue date across all green bonds in the group that share the same issue date. Note that the demand of municipal green bonds on the issue date can be captured by their yield on the same date.

Yield on issue date may display persistence due to gradual macro-financial adjustments and structural issuance patterns, while short-term market shocks and pricing noise can generate temporary dependence on outcomes. The sovereign auction demand in Japan can be proxied by bid-to-cover ratios and carries important informational and liquidity signals (Hattori and Takahashi, 2021) showing that weak auction demand can presage higher yields or reduced liquidity not only domestically, but also in related asset markets, illustrating an investor sentiment or portfolio rebalancing channel. By extension, shifts in Japanese bid-to-cover ratios could meaningfully influence Japanese institutional flows into or out of U.S. municipal bond markets (Jiang and Shimizu, 2023). To capture these dynamics in a parsimonious way, we estimate, for each spread group g, a regression including contemporaneous and lagged covariates, the lagged dependent variable, and the Japanese Treasury bid-to-cover ratio as a separate variable of interest,

$$Y_{g,t} = \alpha_g + \theta_g \,\mathrm{JPNBidCov}_t + \sum_{j=1}^{J} \beta_{g,j}\, X_{j,t} + \sum_{k=1}^{K} \gamma_{g,k}\, X_{k,t-1} + \sum_{\ell=1}^{2} \delta_{g,\ell}\, Y_{g,t-\ell} + \varepsilon_{g,t}, \quad \varepsilon_{g,t} \sim \mathcal{D}(0, \sigma_g^2, \nu_g). \tag{4}$$

Here, $Y_{g,t}$ denotes the bond yield spread for group g at time t, with α_g as the group-specific intercept. The term $\mathrm{JPNBidCov}_t$ represents the Japanese Treasury bid-to-cover ratio as a key regressor, allowing us to evaluate its distinct role in driving spread dynamics.

[22] Bonds with at least 80 percent positive or negative monthly spreads over the 2016–2024 period are selected for each green bond group to ensure that only bonds with consistently stable spread behavior across the intended horizon are included.

[23] Heterogeneity in attributes not included in the group's defining rule is intentionally ignored to remain faithful to the grouping logic implied by the dominant ARL attribute.

The vector $X_{j,t}$ collects the contemporaneous macro-financial covariates such as the Fed Funds rate, DXY, SP500, Nikkei, exchange rate, CPI measures, trade deficit, and the U.S. bid-to-cover ratio, while $X_{k,t-1}$ denotes their one-period lags.[24] Persistence in spreads is captured by the autoregressive components $\delta_{g,1}$ and $\delta_{g,2}$ on the first and second lags of the dependent variable, $Y_{g,t-1}$ and $Y_{g,t-2}$[25], respectively. The error term $\varepsilon_{g,t}$ follows either a Normal or a Student-t distribution, with ν_g representing the estimated degrees of freedom parameter, which can accommodate heavy-tailed residuals. These variables are chosen to reflect cross-border demand, currency strength, equity risk appetite, price level dynamics, and policy stance that plausibly comove with municipal issuance conditions.

Issuance dates are event-driven and irregular, whereas covariates arrive at daily, monthly, or quarterly frequencies. Each issuance observation is paired with the most recent prior observation of each covariate to preserve causal timing. All series are pre-whitened by removing their sample mean and scaling by their sample standard deviation to mitigate scale effects and improve numerical stability. No temporal interpolation is applied; the irregular spacing implied by the issuance timing is retained.

In Appendix L, model adequacy is evaluated using residual autocorrelation diagnostics, including Ljung–Box tests on both standardized and squared residuals to detect any remaining serial dependence, Breusch-Pagan tests to assess homoscedasticity, and Shapiro-Wilk test to evaluate normality of the error terms. In addition, diagnostic plots are used to assess potential heteroskedasticity and deviations from normality. Multicollinearity is also examined, with the heatmap indicating that there is no evidence of severe collinearity after ARL-based partitioning.

5.2. Descriptive statistics

Table 4 summarizes the descriptive statistics for the variables for green bond groups selected by ARL. We consider the rules of first-, second-, and third-order associated with

[24] We exclude the Bank of Japan rate from the analysis because this variable exhibits limited variability, particularly in the early years of the sample period, which prevents the regression model from converging to a stable coefficient estimate for it.

[25] The interval analysis of issuance dates (see Appendix L) reveals irregular patterns in the timing of observations. Thus, we include two lags of the response variable to capture this irregular frequency and to mitigate autocorrelation in the residuals, while keeping the model parsimonious in terms of the number of covariates.

positive yield spreads, namely P1, P2, P3, respectively, and the rules of first-, second-, and third-order associated with negative yield spreads, namely N1, N2, N3, respectively. Since we match the independent variables to the issue date of green bonds for each group, the summary statistics of these variables is expected to differ within the bond groups.[26] According to Tables 2 and 3, for positive green bond yield spreads, federal taxable is the strongest first-order rule, at-par/federal taxable is the strongest second-order rule, and revenue bonds/at-par/federal taxable is the strongest third-order rule. For negative green bond yield spreads, spread on issue date less than 17 is the strongest first-order rule, non-callable/spread on issue date less than 17 is the strongest second-order rule, and New Money/non-callable/spread on issue date less than 17 is the strongest third-order rule.

We make the following observations regarding the descriptive statistics of key variables across the green bond groups. Yields on issue date are higher for the first-order positive spread groups and gradually decline in P2 and P3, whereas the yields on the issue date for the negative spread groups (N1–N3) display consistently lower yields (compared to the positive spreads) with minor variation across the three groups. The Japanese Treasury bid-to-cover ratios are relatively stable across positive and negative groups, with slightly higher averages in P2–P3 than P1 and in N2–N3 than N1. The U.S. Treasury bid-to-cover ratios are almost identical across all groups, showing little distinction between positive and negative spreads. The other control variables also show in general consistent descriptive statistics across the green bond groups, with negative spreads displaying higher means, e.g. the CPI in Japan is approximately double on average for negative spreads groups compared to positive spread groups. Note that typically the number of bonds decreases as we increase the order of the rules. These observations confirm the importance of screening process for green bond markets[27].

[26]The time intervals for the six bond groups are 2010-06-16 to 2022-12-15, 2010-09-09 to 2022-12-21, 2010-06-16 to 2022-12-15, 2010-09-09 to 2022-12-21, 2010-08-25 to 2022-04-14, and 2010-09-09 to 2022-12-21 for P1, P2, P3, N1, N2, and N3, respectively. As the available data for JPNBidCov begins on 2015-12-09, this date is set as the starting point of the regression model.

[27]Observed outliers with absolute Z-scores exceeding 2 were removed from the yield on issue date in groups P1 and N1 only, as this threshold provides a balance between removing potential data errors and making the dataset comparable to the other groups by removing extreme values, resulting in the removal of only 9.1% of observations from P1 and 2.2% from N1.

5.3. Effects of demand shocks on green bonds

The results of the regression model Eq. (4) in the six green bond groups are presented in Table 5. The dependent variable is the yield on issue date, which reflects primary market demand: higher issuance yields imply weaker demand, as investors require a discount to absorb bonds, while lower issuance yields indicate stronger demand with investors willing to accept tighter pricing.

For bond groups with positive spreads, we find that the effect of JPN BidCover evolves with rule complexity. For the first-order rule (federal taxable bonds) the coefficient is positive and significant ($+0.22^{**}$), and in second- and third-order rules it remains positive with ($+0.33^{*}$) and ($+0.40^{\cdot}$), respectively. This means that a one-unit increase in the Japanese bid-to-cover ratio is associated with approximately a 0.22%, 0.33%, and 0.40% rise in the yield on issue date for these groups, respectively.

Thus, in these more structured green bond groups (e.g., revenue/at-par/federal taxable bonds), a strong demand in Japanese Treasury auctions is associated with higher issuance yields in U.S. municipal green bonds.[28] This pattern is consistent with demand-pressure premia documented in corporate green primary markets (Caramichael and Rapp, 2024) and with benchmark-driven transmission from sovereign green activity into broader debt markets (Cheng et al., 2024; Ando et al., 2024; Descombes and Szczerbowicz, 2024). It suggests a portfolio rebalancing channel in which strong JGB demand reduces Japanese flows into U.S. municipals, raising issuance yields.

Results for higher-order positive groups (such as P3) should be interpreted with caution. These groups necessarily involve smaller sample sizes ($N < 30$), which reduces statistical power and increases sensitivity to outliers or idiosyncratic issuance events. However, this trade-off is common in the green bond literature, where sharper identification of the "greenium" or demand channels often comes at the cost of reduced sample coverage (Hachenberg and Schiereck, 2018; Zerbib, 2019; Bhanot et al., 2022). Importantly, the patterns observed in the higher-order groups remain consistent with the broader findings from the lower-order and larger-sample groups. This consistency suggests that, while the estimates for P3 and

[28] We assume that California consists a representative sample for the U.S. municipal green bonds.

similar groups should be viewed as indicative rather than definitive, they nonetheless provide evidence of how cross-country demand pressures transmit most strongly into attribute-homogeneous segments of the market.

For negative spread green bond groups, the coefficients remain positive yet smaller than in positive spreads, and their magnitude and statistical significance increases in the highest order rules. In the first- and second-order rules the coefficient is negligible and not statistically significant. However, third-order rules (e.g. non-callable/NewMoney/spread-at-issuance less than 17) become statistically significant ($+0.26^{**}$).[29] These trends for positive and negative spreads align with our BMS results presented in Appendix G.

This implies that bonds that enjoy a negative spread (priced below benchmarks due to strong demand) have their advantage eroded when Japanese Treasury auctions attract stronger bids, as issuance yields rise despite the underlying excess demand. In other words, even oversubscribed negative-spread bonds remain vulnerable to external shocks. This may also suggest limits to the so-called greenium: even when bonds are priced tightly due to strong ESG demand, external liquidity shocks can erode their advantage.

These results show that both positive- and negative-spread bonds are influenced by Japanese auction dynamics. For positive-spread bonds (P1–P3), the evidence clearly indicates strong interest from international investors, particularly Japanese institutions, in federally taxable municipal green bonds. All positive-spread groups, which include federally taxable bonds, display marked sensitivity to Japanese bid-to-cover ratios, confirming this demand channel. The preference stems from the fact that taxable bonds are more attractive to foreign investors, who can benefit from low-cost liquidity and higher spreads without being subject to U.S. tax obligations. In the case of negative-spread bonds (N1–N3), the effect is more pronounced in higher-order, attribute-defined groups, highlighting the value

[29] We conducted further investigation of the negative spread group N3 by estimating additional models based on the second- and third-ranked rules, namely, non-callable/Coupon 5-8.5%/spread-at-issuance less than 17 and non-callable/tax-exempt/spread-at-issuance less than 17, (see Table 3). These rules exhibit similar confidence levels. For (non-callable/Coupon 5-8.5%/spread-at-issuance less than 17, the coefficient on the Japanese Treasury bid-to-cover ratio is 0.1589^{*}, while for non-callable/tax-exempt/spread-at-issuance less than 17 it is 0.0848 (not significant). Thus, as the rule order increases, both statistical and economic significance decline, confirming the robustness of our choice to use first-ranked rules as the grouping criterion. For detailed diagnostic checks, see Appendix K.

of our proposed screening approach, which enables the identification of complex structuring combinations that appeal to a broader spectrum of investors.

The U.S. bid-to-cover ratio is not statistically significant across all groups. The absence of economic and statistical significance for U.S. Treasury auctions suggests that municipal green bond spreads are less sensitive to domestic Treasury demand shocks, likely due to similarity in investor bases and weaker portfolio rebalancing effects compared to foreign sovereign markets. Domestic Treasuries and municipals already share a deep investor base, so auction outcomes do not create strong new rebalancing pressures. Macro-financial control variables provide a benchmark for the relative importance of Japanese government bond auction demand. Lagged issuance yields are consistently important: negative for positive spread groups (e.g., -0.24 in first-order positive spreads and $-0.33^{\cdot}$ in second-order) and positive and highly significant for negative spread groups (e.g., $+0.52^{***}$ in first-order, $+0.51^{***}$ in second-order, and $+0.49^{**}$ in third-order), confirming the strong persistence in primary-market pricing conditions. This persistence may reflect path dependence: yields in positive groups tend to mean revert after spikes, while yields in negative groups reinforce existing pricing momentum. Importantly, the coefficient on Japanese government bond auction demand in third-order negative rules is $+0.26^{**}$, indicating a nontrivial but smaller effect than the autoregressive terms, yet still meaningful in the context of primary pricing.

Other controls show expected patterns. The U.S. Fed Funds Rate effects are generally not statistically significant, though positive in positive groups (e.g., $+0.35$ in P3) and negative in negative groups, consistent with monetary tightening raising yields where demand is weaker but compressing them where demand is structurally strong. The DXY index exerts negative and sometimes significant effects in positive groups (e.g., -0.71^{*} in P2), but is positive and significant in N3 ($+0.62^{**}$), suggesting shifts in global funding costs or risk appetite across spread classifications. The Nikkei Index is consistently negative and highly significant in positive groups (e.g., -2.31^{***} in P2), indicating spillovers from Japanese equity conditions. The USDJPY exchange rate exerts large, positive effects in positive groups (e.g., $+1.63^{***}$ in P2) and in some negative groups (e.g., $+0.70^{**}$ in N2), implying that yen depreciation against the dollar raises U.S. muni yields, consistent with higher hedging costs reducing Japanese investor appetite. These macro–spillover channels are in line with recent connectedness evidence between energy markets and green bonds (Yousaf et al., 2024) and with shifts in investor preference toward green assets during geopolitical episodes (Fiorillo et al., 2024).

In conclusion, this analysis confirms that stronger demand at Japanese Treasury auctions raises issuance yields for U.S. municipal green bonds, with effects up to roughly +0.40 in positive spread groups and $+0.26^{**}$ in third-order negative groups. Compared to other drivers, lagged yields (around +0.5 in negative groups) and USDJPY (above +1 in positive groups) are larger in magnitude, but JGB auction demand remains an economically meaningful cross-border driver. The effects strengthen in higher-order rules, underscoring that structurally defined segments of the muni green bond market are the most exposed to international demand shocks and are consistent with recent evidence on demand pressure, benchmark effects, and evolving sovereign and corporate green premia (Caramichael and Rapp, 2024; Cheng et al., 2024; Descombes and Szczerbowicz, 2024).

6. Conclusion and financial implications

This study delves into the evolving and complicated landscape of green bond markets, particularly focusing on modelling spreads of green bonds and then identifying association attributes of the Californian municipal green bond spreads from a screening perspective. To address the shortcomings of traditional bond matching-based spread methods, we introduce a novel measure of green bond spreads based on the YTM. We find that green bond spreads in California are, on average positive, but reach negative levels after 2022. A screening analysis via a machine learning method, the ARL, to identify combinations of attribute associations reveals that taxable, at-par, and long maturity are key attributes of positive spreads, while negative spreads exhibit more complex interactions with attributes such as yields on issuance, non-callable, at-premium and tax-exempt. A temporal analysis of the strength of these associations shows a fundamental restructuring of the green market post 2022. While until 2022 the market tends to be balanced in terms of the attributes for positive and negative spreads, after 2022 the attributes of negative spreads have weakened. This implies that excessive demand after 2022 drives the negative green bond spread dynamics irrespective of their structuring attributes.

The economic significance of the screening process has been examined by assessing the impact of cross-border shock transmissions into municipal green bonds with particular structural attributes in California, the largest municipal market in U.S.. Using Japanese Government Bond auction demand as an exogenous shock for green bond demand, we demonstrate that green bond groups identified by our ARL screening have distinct responses to this international demand shock. Most importantly, the impact was more pronounced in more attribute-defined bond groups (involving high-order rules) which would not been easily identifiable without this screening exercise.

These results demonstrate the importance of screening practice in green bond markets to navigate its complexities regarding its integration in current financial markets, and its implications in terms of policy and decision-making in asset management. Investors should consider green bonds not as a replacement for conventional bonds, but as a means to diversify their portfolios and capitalize on new investment opportunities. These innovative instruments also offer issuers the opportunity to diversify their debt holder portfolio (Zerbib (2019)). Understanding investor preferences also allows for the tailoring of bond offerings to attract investors and secure better pricing. We conclude with detailed reflections on the financial implications of our findings for investor and issuers.

6.1. Financial implications

The tax status emerges as one of the most influential attributes for green municipal bond markets. For issuers, tax status plays a strategic role in enabling access to diverse investor pools. Taxable green municipals compete directly with corporates and Treasuries and are therefore more attractive to foreign pensions and insurers that are indifferent to U.S. tax benefits, while tax-exempt bonds primarily appeal to high-net-worth and retail domestic investors seeking after-tax yield advantages. Taxable bonds provide flexibility to fund projects that may not qualify for tax-exempt status under federal guidelines, such as private activity bonds or infrastructure initiatives with mixed-use benefits (Environmental Finance (2023)). In addition, taxable bonds attract international buyers or entities less sensitive to U.S. tax considerations, while tax-exempt bonds align with domestic investors focused on environmental and financial alignment often allow them to secure financing at a lower cost of capital. Furthermore, larger issuance sizes with well-structured coupon rates can enhance liquidity and attract diverse investor profiles, reinforcing the appeal of green bonds in competitive debt markets.

The choice of tax status impacts not only the spreads, but also the long-term value proposition of green bonds. Tax-exempt green bonds align particularly well with environmentally focused projects, offering investors a pathway to support sustainable initiatives while optimizing after-tax returns. This dual mandate of achieving financial performance and driving environmental impact underscores the critical role of tax-exempt bonds in aligning capital markets with sustainability goals (International Capital Market Association (2018)).

Pricing strategy, callability, and maturity are attributes that interact in the way they relate to the yield spread dynamics. The issuance of green bonds at par or premium often reflects oversubscription and excess demand over supply at issuance, e.g. premium issuance reflects strong investor demand for green bonds. However, premium versus par is not just a signal of demand. In practice, premium structures also interact with portfolio roll-down strategies and reinvestment risk. For institutional muni investors, premium bonds can behave differently along the curve, influencing secondary market demand and relative value assessments. While premium-issued bonds align with ESG objectives, they require careful assessment of long-term value propositions, particularly for short maturities where roll-down effects may not materialize. For issuers, premium issuance reduces the cost of capital, but may exclude yield-sensitive investors, necessitating a balance between pricing optimization and market accessibility. As noted in Baker et al. (2022), the decision to price green bonds similarly to conventional bonds, despite demand-driven premiums, reflects broader market expectations for transparency and fairness.

Longer maturities amplify the importance of callability and duration. Callable bonds dominate longer maturities, offering issuers flexibility to refinance under favorable conditions, while investors demand higher yields to offset early redemption risks. Callability in long-duration bonds is used to manage funding uncertainties (Environmental Finance (2023)). From an investor's perspective, callable munis also embed negative convexity and reinvestment risk, which traditionally command a clear premium. In ESG-driven markets, however, excess demand may compress this premium, potentially distorting the risk–return balance for institutional portfolios. Duration effects are particularly significant during periods of monetary policy change. Longer durations amplify spread dynamics, especially when the yield curve deviates from flatness. Callable bonds with extended durations often demand higher yields, while non-callable bonds with shorter durations offer stability and narrower spreads (Partridge and Medda (2020)). In municipal markets, long-duration bonds also carry heightened liquidity and horizon-mismatch risks. The recent shift to negative spreads suggests that ESG-driven demand has, at times, eroded the traditional term premium, a development with implications for both pricing efficiency and portfolio construction. The interaction between maturity and green bond attributes has broader implications for investors and issuers. For investors seeking stable cash flows, short-maturity bonds with limited optionality may provide better predictability and alignment with liquidity needs. However, investors with long-term horizons can capitalize on higher spreads associated with long-maturity callable bonds while supporting sustainable infrastructure and ESG-aligned projects. Issuers can leverage longer maturities to align debt repayment schedules with the lifespan of green projects, such as renewable energy installations or water management systems (Climate Bonds Initiative (2024, 2015)).

We also find a regime shift in the municipal green bond market. After 2020, spreads moved structurally into negative territory, indicating that investor demand for ESG-aligned instruments began to dominate pricing. In this new regime, classical bond attributes (such as callability or maturity) lost much of their explanatory power, with tax status remaining the only consistent attribute. Thus, this regime shift means that spreads no longer provide a clean signal of credit or liquidity risk. Instead, they increasingly reflect excess ESG demand, compressing compensation for traditional risks. Investors should adjust portfolio models to avoid misinterpreting negative spreads as indicators of lower fundamental risk. This implies that compensation for traditional risks is compressed, requiring a greater emphasis on reputational and sustainability alignment in portfolio allocation. From an issuer's perspective, this reduces the importance of tailoring bonds around conventional features such as callability or coupon design, since ESG-driven demand supports tighter pricing regardless. From a regulatory perspective, the shift raises concerns about market efficiency, as spreads may no longer provide a clear signal of underlying risk, prompting calls for stronger standards and transparency in green bond issuance.

Declaration of generative AI and AI-assisted technologies in the writing process: While preparing this work, the authors used ChatGPT to improve the manuscript's readability and language. After that, the authors thoroughly reviewed and edited the content, taking full responsibility for the manuscript's content.

References

Adekoya, O.B., Abakah, E.J., Oliyide, J.A., et al., 2023. Factors behind the performance of green bond markets. International Review of Economics & Finance 88, 92–106. doi:10.1016/j.iref.2023.06.015.

Agrawal, R., Imieliński, T., Swami, A., 1993. Mining association rules between sets of items in large databases, in: Proceedings of the 1993 ACM SIGMOD international conference on Management of data, pp. 207–216. doi:10.1145/170035.170072.

Ando, S., Fu, C., Roch, F., Wiriadinata, U., 2024. How large is the sovereign greenium? Oxford Bulletin of Economics and Statistics 86, 1472–1483. doi:10.1111/obes.12619.

Arat, E., Hachenberg, B., Kiesel, F., Schiereck, D., 2023. Greenium, credit rating, and the COVID-19 pandemic. Journal of Asset Management 24, 547–557. doi:10.1057/s41260-023-00320-5.

Baker, M., Bergstresser, D., Serafeim, G., Wurgler, J., 2022. The pricing and ownership of US green bonds. Annual Review of Financial Economics 14, 415–437. doi:10.1146/annurev-financial-111620-014802.

Berdiev, U., 2025. What shapes greenium in bond markets? Evidence from Japan. Economic Modelling 151, 107159. doi:10.1016/j.econmod.2025.107159.

Bhanot, K., Combs, C., Patel, R., 2022. Are there different shades of green? The "greenium" in municipal power bonds. The Journal of Fixed Income 31, 84–99. doi:10.3905/jfi.2022.1.129.

Bour, T., 2019. The green bond premium and non-financial disclosure: Financing the future, or merely greenwashing. Master's thesis, Maastricht University, Maastricht, The Netherlands https://finance-ideas.nl/wp-content/uploads/2019/02/msc.-thesis-tom-bour.pdf.

Bredeson, A., 2024. U.S. Municipal Sustainable Bonds: Projecting Moderate Growth in 2024. Technical Report. S&P Global Ratings. URL: https://www.spglobal.com/_assets/documents/ratings/research/101593185.pdf.

Brennan, M., MacLean, C., 2018. Growing the U.S. green bond market: Volume 2: Actionable strategies and solutions. Milken Institute Financial Innovations Lab. https://www.treasurer.ca.gov/growing-the-u.s.-green-bond-mkt-vol2-final.pdf.

California Green Bond Market Development Committee, 2023. California Green Bond Market Development Committee: Recommended Approach to Municipal Green Bond Disclosure. Technical Report. California Green Bond Market Development Committee. https://www.climatebonds.net/certification.

Caramichael, J., Rapp, A.C., 2024. The green corporate bond issuance premium. Journal of Banking & Finance 162, 107126. doi:10.1016/j.jbankfin.2024.107126.

Cecchetti, S.G., Hooper, P., Kasman, B.C., Schoenholtz, K.L., Watson, M.W., 2007. Understanding the evolving inflation process, in: U.S. Monetary Policy Forum, pp. 5–23. https://www.princeton.edu/~mwatson/papers/USMPF_Report_July_2007.pdf.

Chang, X., Hu, X., Shen, R., 2024. Local political preferences and green municipal bonds. Available at SSRN: https://ssrn.com/abstract=4973065.

Chen, Y., Shi, G., Hou, G., 2024. Time-frequency connectedness between green bonds and conventional financial markets: Evidence from China. Discrete Dynamics in Nature and Society 2024, 6655845. doi:10.1155/2024/6655845.

Cheng, G., Ehlers, T., Packer, F., Xiao, Y., 2024. Sovereign green bonds: A catalyst for sustainable debt market development? International Monetary Fund. URL: https://www.imf.org/en/Publications/WP/Issues/2024/06/14/Sovereign-Green-Bonds-A-Catalyst-for-Sustainable-Debt-Market-Development-550527.

Chiang, J., 2023. Growing the U.S. green bond market. Volume 1: The barriers and challenges. California State Treasurer. https://www.treasurer.ca.gov/greenbonds/publications/reports/green_bond_market_01.pdf.

Climate Bonds Initiative, 2015. Scaling up Green Bond Markets for Sustainable Development. Public Sector Guide. Climate Bonds Initiative. https://www.climatebonds.net/files/files/GB-Public_Sector_Guide-Final-1A.pdf.

Climate Bonds Initiative, 2024. Sustainable Debt Market Summary Q1 2024. Market Report. Climate Bonds Initiative. https://www.climatebonds.net/files/reports/cbi_mr_q1_2024_01e_1.pdf.

Climate Bonds Initiative, 2025. Sustainable debt: Global state of the market Q1 2025. URL: https://www.climatebonds.net/data-insights/publications/sustainable-debt-global-state-market-q1-2025.

Dai, L., Huang, C., Yu, C., Gu, S., 2024. A novel discovery model for revealing substitution relationships from international stock markets: With association rule analysis. Heliyon 10. doi:10.1016/j.heliyon.2024.e38774.

De Vincentiis, P., Abis, D., 2025. Non-identical twins: Evidence on greenium in the German treasury bond market. Research in International Business and Finance 79, 103057. doi:10.1016/j.ribaf.2025.103057.

Descombes, T., Szczerbowicz, U., 2024. Do green sovereign bonds benefit from a green premium?[les obligations souveraines vertes bénéficient–elles d'une prime verte?]. Eco Notepad (in progress) doi:https://ideas.repec.org/a/bfr/econot/380.html.

Doran, M., Tanner, J., 2019. Critical challenges facing the green bond market. London: Baker McKenzie. https://www.bakermckenzie.com/-/media/files/insight/publications/2019/09/iflr--green-bonds-%28002%29.pdf.

Dorfleitner, G., Eckberg, J., Utz, S., 2023. Greenness ratings and green bond liquidity. Finance Research Letters 55, 103869. doi:10.1016/j.frl.2023.103869.

Dragotto, M., Dufour, A., Varotto, S., 2025. Greenium fluctuations and climate awareness in the corporate bond market. International Review of Financial Analysis 105, 104281. doi:10.1016/j.irfa.2025.104281.

Ejaz, R., Ashraf, S., Hassan, A., Gupta, A., 2022. An empirical investigation of market risk, dependence structure, and portfolio management between green bonds and international financial markets. Journal of Cleaner Production 365, 132666. doi:10.1016/j.jclepro.2022.132666.

Environmental Finance, 2023. Municipal Green Bond Yield Behaviour. Available online: https://www.environmental-finance.com.

Fang, F., Si, D.K., Hu, D., 2023. Green bond spread effect of unconventional monetary policy: Evidence from China. Economic Analysis and Policy 80, 398–413. doi:10.1016/j.eap.2023.08.019.

Fatica, S., Panzica, R., 2021. Green bonds as a tool against climate change? Business Strategy and the Environment 30, 2688–2701. doi:10.1002/bse.2771.

Fatica, S., Panzica, R., Rancan, M., 2021. The pricing of green bonds: Are financial institutions special? Journal of Financial Stability 54, 100873. doi:10.1016/j.jfs.2021.100873.

Febi, W., Schäfer, D., Stephan, A., Sun, C., 2018. The impact of liquidity risk on the yield spread of green bonds. Finance Research Letters 27, 53–59. doi:10.1016/j.frl.2018.02.025.

Financial Times, 2025. Historic drop in Japan bond auction demand signals global strain. Financial Times URL: https://www.ft.com/content/f1ecc480-5db6-4a11-9f21-f1236fa1552f.

Fiorillo, P., Meles, A., Salerno, D., Verdoliva, V., 2024. Geopolitical turmoil and investor green preference: Evidence from the corporate bond market. Journal of International Money and Finance 149, 103218. doi:10.1016/j.jimonfin.2024.103218.

Flammer, C., 2021. Corporate green bonds. Journal of Financial Economics 142, 499–516. doi:10.1016/j.jfineco.2021.01.010.

Gao, L., Guo, K., Wei, X., 2023. Dynamic relationship between green bonds and major financial asset markets from the perspective of climate change. Frontiers in Environmental Science 10. doi:10.3389/fenvs.2022.1109796.

García, C.J., Herrero, B., Miralles-Quirós, J.L., del Mar Mirallles-Quirós, M., 2023. Exploring the determinants of corporate green bond issuance and its environmental implication: The role of corporate board. Technological Forecasting and Social Change 189, 122379. doi:10.1016/j.techfore.2023.122379.

Gyamerah, S.A., Asare, C., 2024. A critical review of the impact of uncertainties on green bonds. Green Finance 6, 78. doi:10.3934/GF.2024004.

Hachenberg, B., Schiereck, D., 2018. Are green bonds priced differently from conventional bonds? Journal of Asset Management 19, 371–383. doi:10.1057/s41260-018-0088-5.

Hattori, T., Takahashi, S., 2021. Discriminatory versus uniform auctions: Evidence from JGB market. Research and Co-ordination Department, Policy Research Institute. doi:https://www.mof.go.jp/pri/research/discussion_paper/ron344.pdf.

Huang, D., Liang, T., Hu, S., Loughney, S., Wang, J., 2023. Characteristics analysis of intercontinental sea accidents using weighted association rule mining: Evidence from the Mediterranean Sea and Black Sea. Ocean Engineering 287, 115839. doi:10.1016/j.oceaneng.2023.115839.

International Capital Market Association, 2018. Green Bond Principles: Voluntary Process Guidelines for Issuing Green Bonds. Guidelines. ICMA. https://www.icmagroup.org/assets/documents/regulatory/green-bonds/green-bonds-principles-june-2018-270520.pdf.

Jiang, Y., Shimizu, S., 2023. Linkages among the foreign exchange, stock, and bond markets in Japan and the United States, in: Causal Analysis Workshop Series, PMLR. pp. 1–19. doi:https://proceedings.mlr.press/v223/jiang23a.

Kapraun, J., Latino, C., Scheins, C., Schlag, C., 2021. (in)-credibly green: which bonds trade at a green bond premium?, in: Proceedings of Paris December 2019 Finance Meeting EUROFIDAI-ESSEC. doi:10.2139/ssrn.3347337.

Karpf, A., Mandel, A., 2018. The changing value of the 'green' label on the U.S. municipal bond market. Nature Climate Change 8, 161–165. doi:10.1038/s41558-017-0062-0.

Khamis, M., Aassouli, D., 2023. The eligibility of green bonds as safe haven assets: A systematic review. Sustainability 15, 6841. doi:10.3390/su15086841.

Kocaarslan, B., 2021. How does the reserve currency (US dollar) affect the diversification capacity of green bond investments? Journal of Cleaner Production 307, 127275. doi:10.1016/j.jclepro.2021.127275.

Larcker, D.F., Watts, E.M., 2020. Where's the greenium? Journal of Accounting and Economics 69, 101312. doi:10.1016/j.jacceco.2020.101312.

Li, H., Zhou, D., Hu, J., Guo, L., 2022. Dynamic linkages among oil price, green bond, carbon market and low-carbon footprint company stock price: Evidence from the TVP-VAR model. Energy Reports 8, 11249–11258. doi:10.1016/j.egyr.2022.08.230.

Löffler, K.U., Petreski, A., Stephan, A., 2021. Drivers of green bond issuance and new evidence on the "greenium". Eurasian Economic Review 11, 1–24. doi:10.1007/s40822-020-00165-y.

Lombardi Netto, A., Salomon, V.A.P., Ortiz Barrios, M.A., 2021. Multi-criteria analysis of green bonds: Hybrid multi-method applications. Sustainability 13, 10512. doi:10.3390/su131910512.

Mertzanis, C., Tebourbi, I., 2025. Geopolitical risk and global green bond market growth. European Financial Management 31, 26–71. doi:10.1111/eufm.12484.

Moro, A., Zaghini, A., 2025. The green sin: how exchange rate volatility and financial openness affect green premia. Review of Finance , 1189–1217.doi:10.1093/rof/rfaf024.

Naeem, M.A., Karim, S., Uddin, G.S., Junttila, J., 2022. Small fish in big ponds: Connections of green finance assets to commodity and sectoral stock markets. International Review of Financial Analysis 83, 102283. doi:10.1016/j.irfa.2022.102283.

Naeem, M.A., Nguyen, T.T.H., Nepal, R., Ngo, Q.T., Taghizadeh-Hesary, F., 2021. Asymmetric relationship between green bonds and commodities: Evidence from extreme quantile approach. Finance Research Letters 43, 101983. doi:10.1016/j.frl.2021.101983.

Nguyen, T.T.H., Naeem, M.A., Balli, F., Balli, H.O., Vo, X.V., 2021. Time-frequency comovement among green bonds, stocks, commodities, clean energy, and conventional bonds. Finance Research Letters 40, 101739. doi:10.1016/j.frl.2020.101739.

OECD, 2017. Barriers, policy actions and options for green bond market development and growth, in: Mobilising bond markets for a low-carbon transition. OECD Publishing, Paris. doi:10.1787/9789264272323-5-en.

Papavassiliou, E., Topaloglou, N., Zenios, S.A., 2025. Do green bonds provide diversification benefits? The need for tax incentives. Annals of Operations Research doi:10.1007/s10479-025-06501-2.

Partridge, C., Medda, F., 2018. Green premium in the primary and secondary U.S. municipal bond markets. Available at SSRN: https://ssrn.com/abstract=3237032.

Partridge, C., Medda, F.R., 2020. The evolution of pricing performance of green municipal bonds. Journal of Sustainable Finance & Investment 10, 44–64. doi:10.1080/20430795.2019.1661187.

Pham, L., 2021. Frequency connectedness and cross-quantile dependence between green bond and green equity markets. Energy Economics 98, 105257. doi:10.1016/j.eneco.2021.105257.

Rehman, M.U., Raheem, I.D., Zeitun, R., Vo, X.V., Ahmad, N., 2023. Do oil shocks affect the green bond market? Energy Economics 117, 106429. doi:10.1016/j.eneco.2022.106429.

Rizvi, S.K.A., Naqvi, B., Mirza, N., Umar, M., 2022. Safe haven properties of green, Islamic, and crypto assets and investor's proclivity towards treasury and gold. Energy Economics 115, 106396. doi:10.1016/j.eneco.2022.106396.

Shinde, A.A., 2021. Green bonds an investment tool for resilient future: Helping to achieve circular economy business models. Master's thesis. University of Waterloo. http://hdl.handle.net/10012/17676.

Sojoudi, M., Bernard, C., Dupuy, P., Peters, G.W., 2025. Green spread of U.S. municipal bonds. Annals of Operations Research doi:10.1007/s10479-025-06479-x.

Srivastava, T., Mullick, I., Bedi, J., 2024. Association mining based deep learning approach for financial time-series forecasting. Applied Soft Computing 155, 111469. doi:10.1016/j.asoc.2024.111469.

Su, Y.H., Rizvi, S.K.A., Umar, M., Chang, H., 2023. Unveiling the relationship between oil and green bonds: Spillover dynamics and implications. Energy Economics 127, 107043. doi:10.1016/j.eneco.2023.107043.

Tan, X., Dong, H., Liu, Y., Su, X., Li, Z., 2022. Green bonds and corporate performance: A potential way to achieve green recovery. Renewable Energy 200, 59–68. doi:10.1016/j.renene.2022.09.109.

The Economic Times, 2025. Japan 30-year bond auction bid-to-cover ratio 2.92, lowest since december 2023. The Economic Times URL: https://economictimes.indiatimes.com/markets/bonds/japan-30-year-bond-auction-bid-to-cover-ratio-2-92-lowest-since-december-2023/articleshow/121637687.cms.

The Wall Street Journal, 2025. Japan's auction of 40-year bonds shows weak demand amid rise in superlong yields. The Wall Street Journal URL: https://www.wsj.com/economy/japans-auction-of-40-year-bonds-shows-weak-demand-amid-rise-in-superlong-yields-d9e46e87.

Tiwari, A.K., Abakah, E.J.A., Shao, X., Le, T.L., Gyamfi, M.N., 2023. Financial technology stocks, green financial assets, and energy markets: A quantile causality and dependence analysis. Energy Economics 118, 106498. doi:10.1016/j.eneco.2022.106498.

U.S. Environmental Protection Agency, 2024. Municipal bonds and green bonds. URL: https://www.epa.gov/statelocalenergy/municipal-bonds-and-green-bonds.

Wang, C., 2022. The cross-section of municipal bond returns. Brookings Papers on Economic Activity URL: https://www.brookings.edu/wp-content/uploads/2022/06/MKT-24259-SSRN-RP_The-Cross-Section-of-Municipal-Bond-Returns_27fs_20220711.pdf.

Wang, J., Mishra, S., Sharif, A., Chen, H., 2024. Dynamic spillover connectedness among green finance and policy uncertainty: Evidence from QVAR network approach. Energy Economics 131, 107330. doi:10.1016/j.eneco.2024.107330.

Wang, Y., Zhang, K., Cui, Q., Delgado, F., 2020. Bond index approach to the evaluation of transportation P3 market in the U.S. Transportation Research Record 2674, 399–409. doi:10.1177/0361198120919395.

Wang, Y., Zhao, X., Shang, J., 2025. Dynamic risk spillover in green financial markets: A wavelet frequency analysis from China. Energy Economics 143, 108301. doi:10.1016/j.eneco.2025.108301.

Yang, Y., Wu, Y., 2025. Research on association analysis between electricity consumption behaviors and weather factors based on MapReduce. Scientific Reports 15, 15963. doi:10.1038/s41598-025-00602-5.

Yousaf, I., Mensi, W., Vo, X.V., Kang, S.H., 2024. Dynamic spillovers and connectedness between crude oil and green bond markets. Resources Policy 89, 104594. doi:10.1016/j.resourpol.2023.104594.

Zerbib, O.D., 2019. The effect of pro-environmental preferences on bond prices: Evidence from green bonds. Journal of Banking & Finance 98, 39–60. doi:10.1016/j.jbankfin.2018.10.012.

Zhang, R., Li, Y., Liu, Y., 2021. Green bond issuance and corporate cost of capital. Pacific-Basin Finance Journal 69, 101626. doi:10.1016/j.pacfin.2021.101626.

Table 1: Descriptive statistics of green bond yield spreads in California (2016-2024)

	Descriptive Statistics						
Year	Min	1st Qu.	Median	Mean	3rd Qu.	Max	St. dev.
2016	-1.0100	0.3800	0.6900	0.7350	0.9200	4.1200	0.6130
2017	-1.6100	0.3200	0.6200	0.6720	0.8400	3.7900	0.7350
2018	-2.0100	-0.1200	0.3700	0.3670	0.6300	3.7400	0.7620
2019	-1.7000	-0.0900	0.5000	0.4420	0.7600	4.3500	0.7900
2020	-1.5000	0.4900	0.9700	0.9630	1.3400	7.8000	0.8170
2021	-2.1400	-0.0100	0.3900	0.4190	0.7100	5.8100	0.7160
2022	-2.9000	-0.3100	0.2400	0.1560	0.6000	5.5100	0.7400
2023	-6.5800	-1.0100	-0.3900	-0.4110	0.1200	4.2800	0.8310
2024	-3.3200	-1.0200	-0.4800	-0.4810	0.0400	2.4600	0.7250
Total	-6.5800	-0.5600	0.0400	0.0140	0.6300	7.8000	0.9240

Table 2: The support, confidence and lift of first-order attribute associations of positive and negative green bond yield spreads.

Rank	Rule	Support	Confidence	Lift
	Positive Spread ($S(+)$)			
1	{Tax : FED TAXABLE/ST TAX-EXEMPT}	0.1794	0.9979	1.8456
2	{Pricing TYP : At Par}	0.1614	0.9801	1.8126
3	{S OID : Higher than 100}	0.1881	0.8225	1.5211
4	{R Ys to Maturity : Higher than 14.4}	0.1967	0.7862	1.4540
5	{Y_OID : Higher than 3.2}	0.1843	0.7845	1.4509
6	{Maturity OID : Higher than 17}	0.1903	0.7540	1.3944
7	{S OID : 57_100}	0.1659	0.6962	1.2875
8	{Maturity OID : 12.3_17}	0.1658	0.6760	1.2503
9	{DU_Adj_MID : Higher than 7}	0.1658	0.6683	1.2359
10	{Y_OID : 2.4_3.2}	0.1670	0.6592	1.2192
11	{Call : Callable}	0.4174	0.6530	1.2077
12	{R Ys to Maturity : 9.4_14.4}	0.1592	0.6467	1.1960
13	{Active years : Less than 1.1}	0.1565	0.6309	1.1668
14	{Self Rep. Gr. : Not labelled}	0.1387	0.6199	1.1464
15	{Issued Amt : Higher than 16}	0.1485	0.6057	1.1201
	Negative Spread ($S(-)$)			
1	{S OID : Less than 17}	0.1991	0.8335	1.8263
2	{Y_OID : Less than 1.7}	0.1914	0.7469	1.6365
3	{Maturity OID : Less than 8}	0.1781	0.7080	1.5512
4	{R Ys to Maturity : Less than 4.7}	0.1743	0.6921	1.5165
5	{Call : Non-callable}	0.2367	0.6562	1.4377
6	{Pricing TYP : At Premium}	0.4263	0.5791	1.2688
7	{R Ys to Maturity : 4.7_9.4}	0.1432	0.5688	1.2463
8	{Tax : FED & ST TAX-EXEMPT}	0.4385	0.5637	1.2352
9	{Maturity OID : 8_12.3}	0.1382	0.5511	1.2074
10	{CPN : 5_8.5(%)}	0.2726	0.5468	1.1981
11	{S OID : 17_57}	0.1250	0.5254	1.1512
12	{DU_Adj_MID : Less than 2.8}	0.1247	0.5199	1.1391
13	{DU_Adj_MID : 4.8_7}	0.1282	0.5167	1.1321
14	{Issued Amt : Less than 14}	0.1280	0.5121	1.1221
15	{Muni Issued Size : 17_18.7}	0.1266	0.5102	1.1179

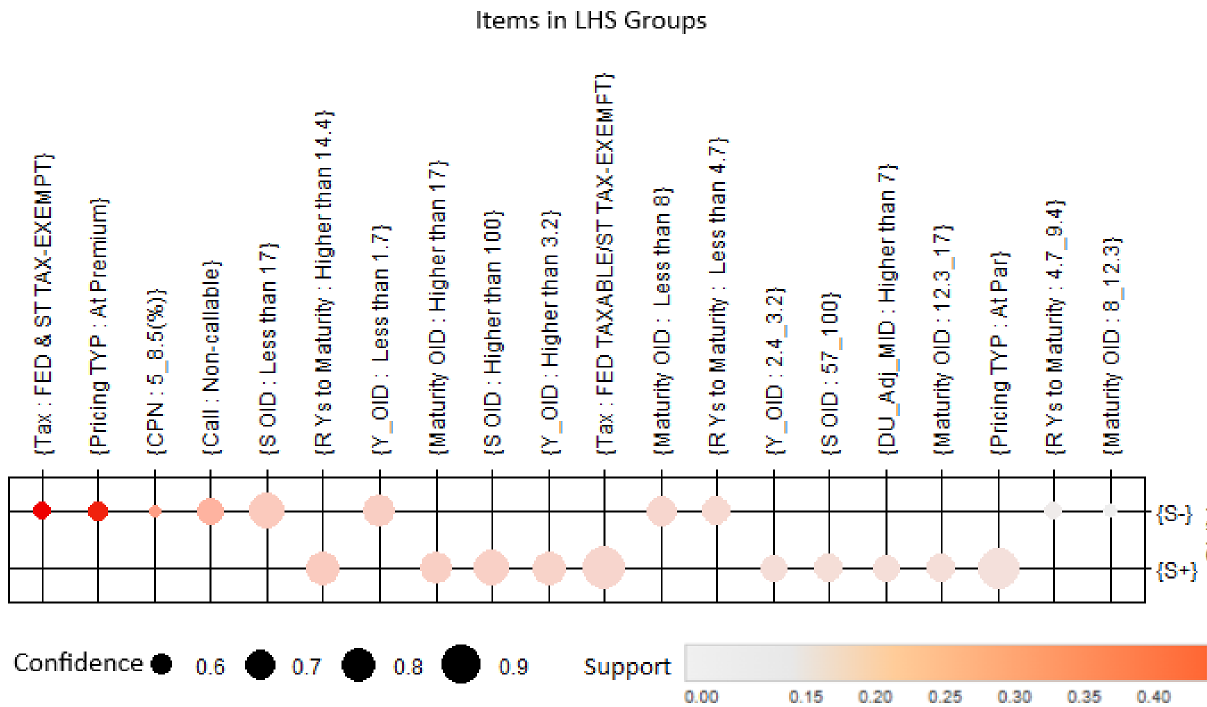


Figure 2: **One state attribute rules for positive and negative green bond spreads based on YTM**. The figure displays the one state attribute rules for positive and negative green bond spreads based on YTM in California. The circle size represents the confidence level of the associations, and color intensity indicates its support.

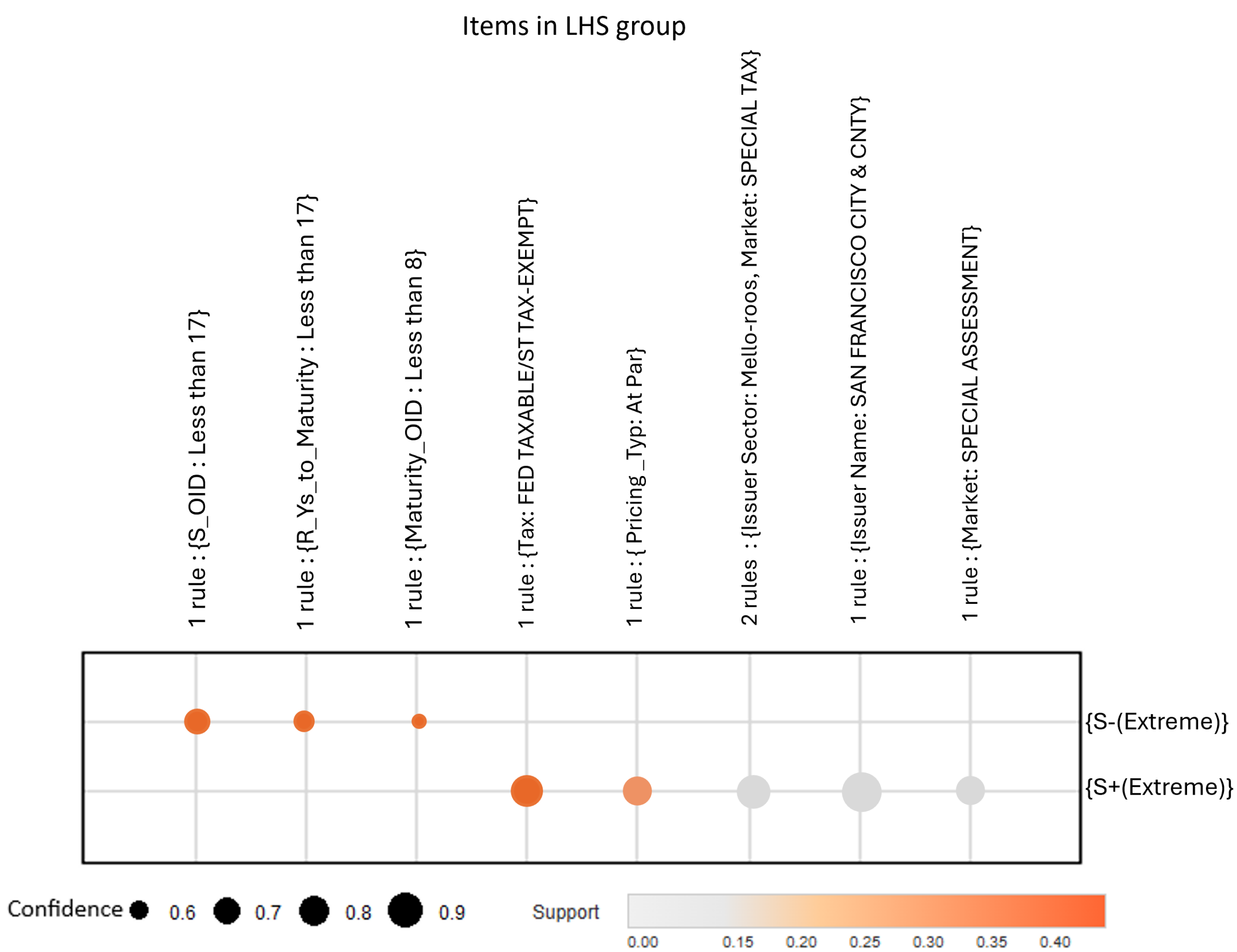
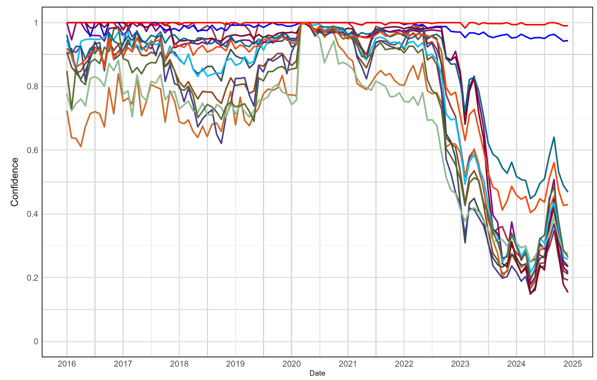
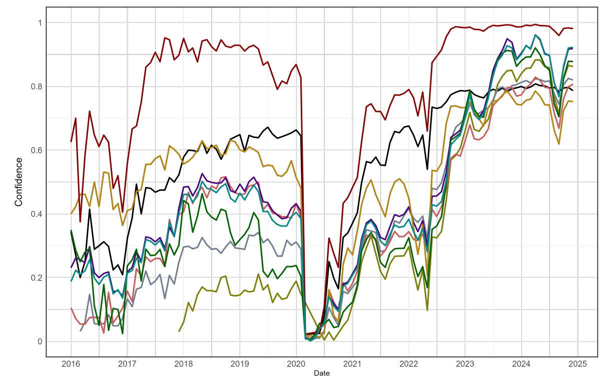


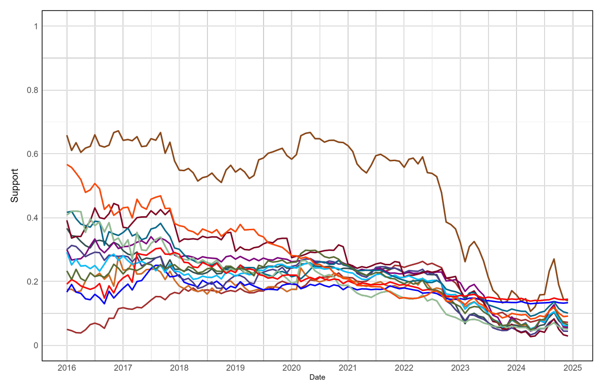
Figure 3: One state attribute rules for extreme positive and negative spread.
The figure displays the one state attribute rules for positive and negative green bond spreads based on YTM in California. The circle size represents the confidence level of the associations, and color intensity indicates its support.



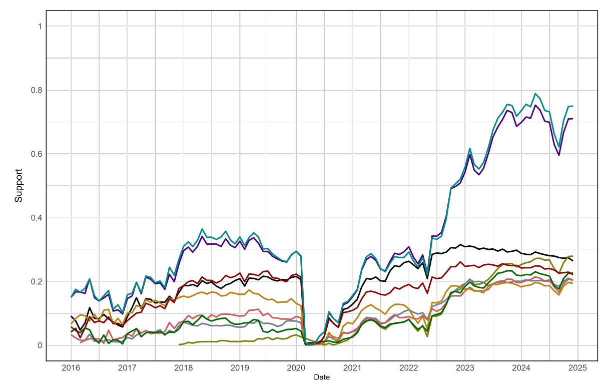
(a) Positive Spread - Confidence



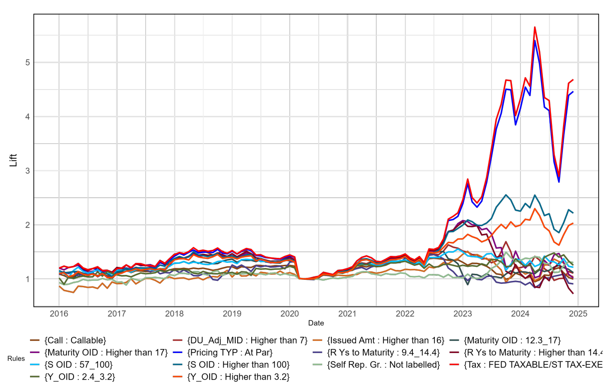
(b) Negative Spread - Confidence



(c) Positive Spread - Support



(d) Negative Spread - Support



(e) Positive Spread - Lift

(f) Negative Spread - Lift

Figure 4: Temporal evolution of confidence, support, and lift for positive (left) and negative (right) green bond yield-spread rules. Each row tracks a different association-rule metric over time: the top row shows rule confidence, the middle row shows rule support, and the bottom row shows rule lift. Within each panel, colored lines correspond to the ten highest-ranked antecedent conditions for positive spreads (left panels) and negative spreads (right panels).

Table 3: The support, confidence and lift of higher-order attribute associations of positive and negative green bond yield spreads.

LHS	Support	Confidence	Lift
Positive Spread (S(+))			
Second-order			
Pricing TYP : At Par, Tax : FED TAXABLE/ST TAX-EXEMPT	0.1550	0.9980	1.8460
Market : REVENUE BONDS, Tax : FED TAXABLE/ST TAX-EXEMPT	0.1100	0.9980	1.8460
BB_rating : Not_Rated, Tax : FED TAXABLE/ST TAX-EXEMPT	0.1200	0.9980	1.8460
Self Rep. Gr. : YES, Tax : FED TAXABLE/ST TAX-EXEMPT	0.1080	0.9980	1.8450
BB_rating : Not_Rated, Pricing TYP : At Par	0.1040	0.9820	1.8170
Third-order			
Market : REVENUE BONDS, Pricing TYP : At Par, Tax : FED TAXABLE/ST TAX-EXEMPT	0.1020	0.9980	1.8450
Negative Spread (S(−))			
Second-order			
Call : Non-callable, S OID : Less than 17	0.1640	0.8980	1.9680
R Ys to Maturity : Less than 4.7, S OID : Less than 17	0.1210	0.8920	1.9540
Maturity OID : Less than 8, S OID : Less than 17	0.1250	0.8870	1.9440
Call : Non-callable, Tax : FED & ST TAX-EXEMPT	0.2250	0.8860	1.9420
R Ys to Maturity : Less than 4.7, Tax : FED & ST TAX-EXEMPT	0.1650	0.8790	1.9270
Third-order			
Call : Non-callable, FIN. TYP : NEW MONEY, S OID : Less than 17	0.1100	0.9090	1.9910
Call : Non-callable, CPN : 5_8.5(%), S OID : Less than 17	0.1210	0.9050	1.9840
Call : Non-callable, S OID : Less than 17, Tax : FED & ST TAX-EXEMPT	0.1630	0.9040	1.9800
Call : Non-callable, Pricing TYP : At Premium, S OID : Less than 17	0.1610	0.9020	1.9770
Call : Non-callable, R Ys to Maturity : Less than 4.7, S OID : Less than 17	0.1130	0.9010	1.9730
Fourth-order			
Call : Non-callable, FIN. TYP : NEW MONEY, S OID : Less than 17, Tax : FED & ST TAX-EXEMPT	0.1090	0.9120	1.9980
Call : Non-callable, FIN. TYP : NEW MONEY, Pricing TYP : At Premium, S OID : Less than 17	0.1070	0.9100	1.9940
Call : Non-callable, R Ys to Maturity : Less than 4.7, S OID : Less than 17, Tax : FED & ST TAX-EXEMPT	0.1130	0.9070	1.9880
Call : Non-callable, CPN : 5_8.5(%), R Ys to Maturity : Less than 4.7, Tax : FED & ST TAX-EXEMPT	0.1030	0.9060	1.9850
Call : Non-callable, Pricing TYP : At Premium, R Ys to Maturity : Less than 4.7, S OID : Less than 17	0.1110	0.9060	1.9850

Table 4: Descriptive statistics for all variables across six bond groups. P1, P2, P3 represent positive spread rules of first-, second- and third-order, respectively, while N1, N2, N3 represent negative spread rules of first-, second- and third-order, respectively. Statistics are calculated using non pre-whitened data.

		P1	P2	P3	N1	N2	N3
YIELD_ON_ISSUE_DATE	Mean	3.2953	2.8309	2.7765	1.4713	1.4231	1.4656
	SD	1.5737	1.0788	1.0215	0.7571	0.7201	0.7553
	Min	0.7270	0.7270	0.7270	0.1750	0.1800	0.1800
	Max	7.7935	5.5840	4.8420	3.1500	3.1500	3.1500
JPN_Treasury_BidCover	Mean	3.3462	3.4094	3.4218	3.3724	3.3731	3.3992
	SD	0.4219	0.4170	0.3544	0.3830	0.3924	0.4029
	Min	2.2140	2.2140	2.8780	2.6070	2.3320	2.6070
	Max	4.1980	4.1980	4.1980	4.1980	4.1980	4.1980
US_Treasury_BidCover	Mean	2.4629	2.4649	2.4644	2.4525	2.4536	2.4620
	SD	0.1124	0.1132	0.0865	0.1429	0.1394	0.1504
	Min	2.2000	2.2000	2.3000	2.1700	2.1700	2.1700
	Max	2.6900	2.6900	2.6200	2.7500	2.7500	2.7500
US_FedFundsRate	Mean	0.8193	0.7935	0.6500	1.1023	1.1431	1.1570
	SD	0.8878	0.9374	0.6475	1.1438	1.1317	1.0903
	Min	0.0500	0.0500	0.0600	0.0500	0.0500	0.0500
	Max	4.3300	4.3300	2.2000	4.3300	4.3300	4.3300
DXY	Mean	96.3863	96.1004	95.4949	96.6581	96.6242	96.4869
	SD	3.4328	3.4979	3.2948	4.9905	4.8289	4.8677
	Min	90.1700	90.1200	90.1200	89.1210	89.1210	89.1210
	Max	104.5580	104.5580	101.7600	111.3530	111.3530	110.5870
SP500_Index	Mean	3150.5368	3281.5611	3257.9907	3440.0880	3374.3457	3420.1878
	SD	815.6507	817.9682	814.2091	801.5535	805.9175	795.7270
	Min	2047.6200	2047.6200	2141.3400	2075.8100	1867.6100	2075.8100
	Max	4696.5600	4696.5600	4696.5600	4704.5400	4704.5400	4704.5400
Nikkei_Index	Mean	23209.8259	23783.8300	23737.8900	24479.5124	24208.9953	24219.5181
	SD	3793.2501	3795.0194	3825.4728	3812.2661	3813.7985	3518.9538
	Min	16405.0100	17235.5000	17235.5000	16498.7600	16498.7600	16666.0500
	Max	30181.2100	30181.2100	30181.2100	30511.7100	30511.7100	30511.7100
CPI_US	Mean	0.2585	0.2784	0.3259	0.3422	0.3233	0.3648
	SD	0.3154	0.3343	0.2809	0.3390	0.3305	0.3269
	Min	-0.8000	-0.8000	-0.1000	-0.8000	-0.8000	-0.8000
	Max	1.1000	1.1000	1.1000	1.1000	1.1000	1.1000
CPI_JP	Mean	0.0732	0.0811	0.0963	0.1627	0.1622	0.1444
	SD	0.2313	0.2379	0.2345	0.2058	0.2102	0.2125
	Min	-0.4000	-0.4000	-0.2000	-0.3000	-0.3000	-0.3000
	Max	0.4000	0.4000	0.4000	0.6000	0.6000	0.5000
TradeDeficit_JP_US	Mean	-5341.9459	-5284.9038	-5411.6663	-5395.7563	-5421.0284	-5424.3637
	SD	1045.9589	1070.3544	1014.5300	936.0149	921.3730	913.9678
	Min	-7215.7100	-7215.7100	-7215.7100	-7349.0300	-7349.0300	-7349.0300
	Max	-1865.7500	-1865.7500	-1865.7500	-2502.6200	-2502.6200	-3473.4700
usdjpy	Mean	111.8783	111.8732	110.5074	114.4104	114.1864	114.5165
	SD	6.8023	6.9358	4.8853	10.3687	10.0581	10.3759
	Min	102.4400	103.7000	103.7000	100.7500	100.7500	103.7400
	Max	136.7700	136.7700	125.2600	146.3100	146.3100	146.3100
Sample Size (N)		42	35	25	89	88	53

Table 5: Lagged regression results for municipal bond yields. P1, P2, P3 represent positive spread groups of orders 1, 2, 3 respectively. N1, N2, N3 represent negative spread groups of orders 1, 2, 3 respectively. Significance levels: *** p<0.001, ** p<0.01, * p<0.05, . p<0.10. Standard errors are shown in parentheses.

	P1	P2	P3	N1	N2	N3
JPN_Treasury_BidCover	0.2247**	0.3279*	0.3970.	0.0645	0.0785	0.2557**
	(0.0781)	(0.1225)	(0.1745)	(0.0625)	(0.0612)	(0.0737)
US_Treasury_BidCover	0.0313	-0.0128	0.0827	0.0041	0.0019	0.0145
	(0.0696)	(0.1142)	(0.1339)	(0.0523)	(0.0511)	(0.0638)
US_FedFundsRate	0.2838.	0.4171	0.3533	-0.2204	-0.2852	-0.2884
	(0.1446)	(0.2530)	(0.3703)	(0.2916)	(0.2758)	(0.2122)
DXY	-0.4128*	-0.7056*	-0.6392.	-0.0472	-0.0378	0.6186**
	(0.1789)	(0.2850)	(0.3184)	(0.1817)	(0.1774)	(0.1846)
SP500_Index	1.8779**	3.0237**	1.5776	-0.3972	-0.4544	0.2717
	(0.5145)	(0.8737)	(1.1499)	(0.3607)	(0.3500)	(0.3118)
Nikkei_Index	-1.4312***	-2.3051***	-1.2035	-0.0775	-0.0142	0.2514
	(0.3182)	(0.5455)	(0.9710)	(0.2679)	(0.2613)	(0.1998)
usdjpy	0.9387***	1.6295***	1.0178**	0.6417*	0.6982**	-0.3215
	(0.2074)	(0.3490)	(0.2739)	(0.2620)	(0.2613)	(0.3212)
CPI_US	-0.1624.	-0.3196*	-0.5755.	0.0519	0.0534	0.0230
	(0.0808)	(0.1414)	(0.2826)	(0.0734)	(0.0717)	(0.0790)
CPI_JP	-0.0576	-0.1201	-0.0378	0.0459	0.0400	0.1144.
	(0.0824)	(0.1342)	(0.1775)	(0.0538)	(0.0534)	(0.0596)
TradeDeficit_JP_US	-0.1295.	-0.2244.	-0.2818	-0.0164	-0.0162	-0.0105
	(0.0669)	(0.1148)	(0.2800)	(0.0530)	(0.0524)	(0.0530)
$\text{YIELD\_ON\_ISSUE\_DATE}_{t-1}$	-0.2419	-0.3345.	-0.3603	0.5213***	0.5092***	0.4920**
	(0.1602)	(0.1653)	(0.2849)	(0.1134)	(0.1103)	(0.1416)
$\text{YIELD\_ON\_ISSUE\_DATE}_{t-2}$	-0.2975	-0.4148.	-0.1679	0.0066	0.0085	0.0611
	(0.1952)	(0.2014)	(0.2305)	(0.1239)	(0.1188)	(0.1351)
$\text{US\_FedFundsRate}_{t-1}$	0.0823	0.2582	0.1589	0.2672	0.3298	0.2644
	(0.1832)	(0.3252)	(0.5145)	(0.2787)	(0.2576)	(0.2268)
DXY_{t-1}	-0.2042	-0.3377	-0.1440	-0.1732	-0.1944	-1.0384***
	(0.1833)	(0.2988)	(0.2971)	(0.1706)	(0.1659)	(0.1698)
SP500_Index_{t-1}	-0.9901.	-1.4242	-0.0518	0.2028	0.2193	-0.6436*
	(0.5088)	(0.8429)	(1.1521)	(0.3422)	(0.3314)	(0.2899)
$\text{Nikkei\_Index}_{t-1}$	0.0003	-0.2114	-0.7151	-0.0604	-0.0975	-0.1852
	(0.3422)	(0.5858)	(0.8230)	(0.2586)	(0.2535)	(0.1919)
usdjpy_{t-1}	-0.2499	-0.2802	0.0383	-0.0430	-0.0652	1.1337***
	(0.1876)	(0.3507)	(0.3825)	(0.2341)	(0.2368)	(0.2972)
Adjusted R^2	0.7369	0.8172	0.7628	0.8413	0.8066	0.9038