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10323
2023

March 2023

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CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp
An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
· from the RePEc website: www.RePEc.org
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CESifo *Working Paper No. 10323*

US Municipal Green Bonds and Financial Integration

Abstract

This paper examines mean and volatility spillovers between four green municipal bonds issued by the US states of California, Colorado, Columbia and Ohio, and the role played by the recent Covid-19 pandemic and the COP policy announcements respectively. Specifically, four-variate VAR-GARCH-BEKK models are estimated which include suitably defined dummies corresponding to those events. Significant dynamic linkages (interdependence) between the four municipal bonds under investigation are found in some cases. Moreover, there is evidence of shifts in the second moment parameters coinciding with the Covid-19 pandemic (contagion), whilst the COP policy announcements do not appear to affect the transmission mechanism between municipal green bond returns and volatilities. On the whole, the evidence suggests weaker linkages, and thus a lower degree of financial integration (and greater portfolio diversification opportunities), during the Covid-19 period, though this is likely to be only a temporary phenomenon.

JEL-Codes: C320, G120, G320.

Keywords: municipal bonds, financial integration, spillovers, multivariate GARCH-BEKK, volatility.

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March 2023

1. Introduction

In recent years ESG (environmental, social and governance) investments based on an ethical approach have become increasingly popular. Of the three pillars of ESG the environmental or green one is by far the largest. Following the publication in 2007 of the United Nations report on Climate Change that identified gas emissions as the main cause of global warming, the first "green bonds" were issued by the European Investment Bank and the World Bank in 2007-8 to fund environmentally sustainable projects and support the transition to low-carbon economies. Since the Paris Agreement of 2015 was signed to address the issue of climate change the issuance of this new type of financial asset has grown exponentially. Climate Bonds' Market Intelligence reported that USD2trillion in green bonds had been issued by the end of Q3 2022; they represent 52.1% of sustainable bond labels (social, sustainability, sustainability-linked and transition), which had reached USD3.5trillion by the same date and account for 5% of all debt issued (see Climate Bonds Initiative, 2022).

Investors have shown considerable interest in this new financial asset, not only because of their increasing awareness of environmental issues, but also because of the portfolio diversification opportunities green bonds could offer given their apparently low correlation with other financial assets (see, e.g., Reboredo, 2018). This issue has been examined in various studies. For instance, Pham (2021) analysed the frequency connectedness and cross-quantile dependence vis-à-vis green equities and found small dependence during normal market conditions and much stronger connectedness during extreme market movements. Broadstock and Chenge (2019) investigated correlations between green and black bonds and found that they are time-varying, being affected by various factors such as volatility, economic policy uncertainty, news etc. Reboredo and Ugolini (2020) estimated a structural VAR model identified through heteroscedasticity and concluded that green bonds are mainly linked to the Treasury and currency markets, less so to other bond markets. Elsayed et al. (2022) used both a wavelet approach and the connectedness measure of Diebold and Yilmaz (2012) and provided evidence of long-run linkages as well as of volatility in the interconnection between green bonds and other financial assets.

Another interesting issue is whether the recent Covid-19 pandemic has affected these relationships. For example, Haciomeroglu et al. (2022) estimated a difference-in-difference model to analyse the linkages between green and "brown" conventional bonds and reported that in the primary (secondary) market there was a larger decline in green (brown) bond returns during the Covid-19 pandemic. It is noteworthy that very few studies have focused on the interactions between different green bonds. A notable exception is the paper by Mensi et al. (2022) that used copulas, CoVar and quantile regression approaches to investigate price spillovers among various categories of green bonds and provided evidence of significant dynamic volatility spillovers that became stronger during the Covid-19 pandemic.

All of the above mentioned studies concern green bonds issued by international organisations, national governments or financial institutions. Much less is known about the municipal green bond market, which is becoming increasingly important – for instance, in the case of the US it now makes up close to 30% of the total US green bond market (see Refinitiv, 2021). Although some aspects such as the pricing and ownership (see Baker et al., 2018) and the use of proceeds (see Friedland, 2020) of municipal green bonds have already been examined, their interactions have yet to be analysed thoroughly. The present study aims to contribute to the literature by shedding new light on this issue. More specifically, it investigates both "interdependence", namely the existence of dynamic linkages, and "contagion", defined as a shift in the return and volatility spillover parameters (see Forbes and Rigobon, 2002; Caporale et al., 2005, 2006; Beirne et al., 2010, 2013), between four major US Municipal Green Bonds issued by the US states of California, Colorado, Columbia, and Ohio. The framework employed for the empirical analysis is a four-variate VAR-GARCH-BEKK model which includes suitably defined dummies to capture possible parameter shifts associated with the Covid-19 pandemic and the COP (Conference of Parties) policy announcements. One of the aims of the analysis is to establish whether the financial linkages in question have become weaker or stronger as a result of the exogenous shock and the policy announcements being considered, and thus whether the degree of financial integration of these markets has changed.

In brief, relative to previous studies the contribution of the present one is threefold: it focuses on the municipal bond market, which has not been explored much before; it uses a framework that examines simultaneously linkages between both municipal bonds returns and their volatilities; it tests for possible parameter shifts to establish whether there have been any changes (in response to either exogenous shocks or policy announcements) in the strength of those linkages, which can be seen as a measure of the degree of financial integration of this specific market. The results indicate that, while the Covid-19 pandemic had an impact on the dynamic linkages between the four green municipal bonds under examination, especially in the case of their second moments, the COP policy announcements did not affect them, neither in the first nor in the second moments. Furthermore, the conditional correlations between the four bonds considered are generally positive, and they are lower in the subsample including the Covid-19 pandemic. On the whole, the evidence of weaker linkages points to a disruption caused by the Covid-19 shock to the process of financial integration for this type of instruments, which is, however, likely to be only temporary: as in the case of other economic and financial variables the effects of this exogenous shock can be expected to vanish over time.

The layout of the paper is as follows. Section 2 outlines the methodology. Section 3 describes the data. Section 4 discusses the empirical results. Section 5 offers some concluding remarks.

2. Methodology

2.1. Basic Model

We represent the first and second moments of municipal green bonds returns using a four-variate VAR-GARCH(1,1) process. In its most general specification the model takes the following form:

$$x_t = \alpha + \beta x_{t-1} + \phi z_{t-1} + e_t \qquad (1)$$

where x_t = (California$_t$, Colorado$_t$, Columbia$_t$, Ohio$_t$), x_{t-1} is a corresponding vector of lagged municipal green bond returns, and $e_t = (e_{1,t}, e_{2,t}, e_{3,t}, e_{4,t})$ is a residual vector. Furthermore, z_{t-1} is the US three-month T-Bill rate, and is used as a proxy for the Fed monetary policy announcements. The parameters of the mean return equations (1) include the constant terms $\alpha = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ and the autoregressive terms $\beta = (\beta_{11}, \beta_{12}, \beta_{13}, \beta_{14} \mid \beta_{21}, \beta_{22}, \beta_{23}, \beta_{24} \mid \beta_{31}, \beta_{32}, \beta_{33}, \beta_{34} \mid \beta_{41}, \beta_{42}, \beta_{43}, \beta_{44})$, which allow for cross-bonds mean return spillovers. The residual vector e_t is four-variate and normally distributed $e_t \mid I_{t-1} \sim (0, H_t)$ with its conditional variance-covariance matrix given by:

$$H_t = \begin{vmatrix} h_{11t} & h_{12t} & h_{13t} & h_{14t} \\ h_{21t} & h_{22t} & h_{23t} & h_{24t} \\ h_{31t} & h_{32t} & h_{33t} & h_{34t} \\ h_{41t} & h_{42t} & h_{43t} & h_{44t} \end{vmatrix} \qquad (2)$$

In the multivariate GARCH(1,1)-BEKK representation proposed by Engle and Kroner (1995), which guarantees by construction that the variance-covariance matrices in the system are positive definite, H_t takes the following form:

$$H_t = C`_0 C_0 + \begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{vmatrix}` \begin{vmatrix} e_{1,t-1}^2 & e_{1,t-1}e_{2,t-1} & e_{1,t-1}e_{3,t-1} & e_{1,t-1}e_{4,t-1} \\ e_{2,t-1}e_{1,t-1} & e_{2,t-1}^2 & e_{2,t-1}e_{3,t-1} & e_{2,t-1}e_{4,t-1} \\ e_{3,t-1}e_{1,t-1} & e_{3,t-1}e_{2,t-1} & e_{3,t-1}^2 & e_{3,t-1}e_{4,t-1} \\ e_{4,t-1}e_{1,t-1} & e_{4,t-1}e_{2,t-1} & e_{4,t-1}e_{3,t-1} & e_{4,t-1}^2 \end{vmatrix} \begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{vmatrix}$$

$$+ \begin{vmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \end{vmatrix}` H_{t-1} \begin{vmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \end{vmatrix} \qquad (3)$$

Equation (3) models the dynamic process of H_t as a linear function of its own past values H_{t-1} and past values of the innovations ($e_{1,t-1}$, $e_{2,t-1}$, $e_{3,t-1}$, $e_{4,t-1}$), allowing for own and cross influences in the conditional variances. The parameters of (3) are given by C_0, which is restricted to be upper triangular, and two matrices A and G whose elements are the a and g coefficients, respectively. The off-diagonal parameters in the latter two matrices capture the volatility spillovers (causality-in-variance) among the four municipal bonds under investigation.

Given a sample of T observations, a vector of unknown parameters[2] θ, and a 4×1 vector of variables x_t, the conditional density function for the model (1) − (3) is:

$$f(x_t \mid I_{t-1}; \theta) = (2\pi)^{-1} \, |H_t|^{-1/2} \, exp(-[e_t' \, (H_t^{-1}) \, e_t] / 2) \qquad (4)$$

The log likelihood function is:

$$Log\text{-}Lik = \Sigma_{t=1}^{T} \log f(x_t \mid I_{t-1}; \theta) \qquad (5)$$

[2] Standard errors (SE) are calculated using the quasi-maximum likelihood method of Bollerslev and Wooldridge (1992), which is robust to the distribution of the underlying residuals.

Furthermore, the adopted BEKK representation guarantees by construction the positive-definiteness of the variance-covariance matrix.

2.2. Mean and Volatility Contagion

Applying the concept of shift contagion (Forbes and Rigobon, 2002) to the analysis of interdependencies in the first and second moments, we define mean and volatility contagion, respectively, as a shift in the transmission of returns and volatility among the municipal green bonds considered either during the Covid-19 pandemic period or around the COP policy announcements. In order to test for such shifts, we include in equations (1) and (3) a dummy *D* that allows the parameters governing the mean and volatility spillovers to change in periods corresponding to the Covid-19 pandemic period (first set of estimates) and the COP policy announcements (second set of estimates). [3] For instance, the equations for the conditional mean and variance of the California bond returns respectively are specified as follows:

$$California_t = \alpha_1 + \beta_{11} California_{t-1} + (\beta_{12} + \beta_{12}^*) Colorado_{t-1} + (\beta_{13} + \beta_{13}^*) Columbia_{t-1} + (\beta_{14} + \beta_{14}^*) Ohio_{t-1} + \phi z_{t-1} + e_{1,t}$$

and

$$\begin{aligned} h_{11,t} = {} & c_{11}^2 + a_{11}^2 e_{1,t-1}^2 + a_{12}^2 e_{2,t-1}^2 + (a_{13} + a_{13}^* \cdot D)^2 e_{3,t-1}^2 \\ & + 2\, a_{11} a_{12} e_{1,t-1} e_{2,t-1} + 2\, a_{11}(a_{13} + a_{13}^* \cdot D)\, e_{1,t-1} e_{3,t-1} + 2\, a_{12}(a_{13} + a_{13}^* \cdot D)\, e_{2,t-1} e_{3,t-1} \\ & + g_{11}^2 h_{11,t-1} + g_{12}^2 h_{22,t-1} + (g_{13} + g_{13}^* \cdot D)^2 h_{33,t-1} \\ & + 2\, g_{11} g_{12} h_{12,t-1} + 2\, g_{11}(g_{13} + g_{13}^* \cdot D)\, h_{13,t-1} + 2\, g_{12}(g_{13} + g_{13}^* \cdot D)\, h_{23,t-1} \end{aligned} \qquad (6)$$

Mean spillovers from Colorado, Columbia and Ohio to California are measured by the parameters β_{12}, β_{13} and β_{14}, whereas β_{12}^*, β_{13}^* and β_{14}^* capture shifts in these parameters during

[3] More precisely, we specify 0-1 dummies with the shift occurring on 20 March 2020 in the case of the Covid-19 dummy, whilst those for the COP policy announcements are defined as being equal to 1 during the COP meetings, and 0 elsewhere. The dates for the meetings considered are the following: COP 21, 30 November to 11 December 2015, Paris, France; COP 22, 7-18 November 2016, Marrakech, Morocco; COP 23, 6 -17 November 2017, Bonn, Germany; COP 24, 2-14 December 2018, Katowice, Poland; COP 25, 2-13 December 2019, Madrid, Spain; COP 26, 31 October - 12 November 2021, Glasgow, UK; COP 27, 6-20 November 2022, Sharm el-Sheikh, Egypt.

the Covid-19 pandemic period and around the COP policy announcements, in turn. Similarly, volatility spillovers from Colorado, Columbia and Ohio to California are measured by the parameters a_{12} and g_{12}, a_{13} and g_{13} and a_{14} and g_{14}, respectively; a_{12}^* and g_{12}^*, a_{13}^* and g_{13}^* and a_{14}^* and g_{14}^* instead capture shifts in these parameters during the Covid-19 pandemic period and around the COP policy announcements.

3. Data Set Description

3.1. Municipal Green Bonds

Green municipal bonds are fixed-income financial instruments issued for raising capital through the debt capital market. The key difference between a green bond and a regular bond is that the former is explicitly labelled as "green" by the issuer, and a commitment is made to use the proceeds of the green bond exclusively to finance or re-finance projects with an environmental benefit. Eligible projects include, but are not limited to, renewable energy, energy efficiency, sustainable waste management, sustainable land use, biodiversity conservation, clean transportation, clean water, and various climate adaptation projects. Municipalities define the kind of green projects they seek to support with green bonds, while clearly stipulating that the proceeds from the green bond sale will be earmarked for green projects or assets. The four-variate VAR-GARCH model outlined in the previous section was estimated for four US municipal green bonds issued by the states of California (California Infrastructure Authority, Clean Water Fund Bonds), Colorado (Lower Colorado River Authority), Columbia (District of Columbia Water & Sewer Authority) and Ohio (American Municipal Power - Ohio). All bonds selected were awarded an A rating, or above, from Fitch.

Table 1 provides a description of the four series along with their Fitch credit ratings. The data are daily and have been collected from Bloomberg; the sample period goes from 2/1/2015 to 2/2/2023, for a total of 2110 observations. Percentage changes are used for the estimation of the models. Figure 1 displays all four series. In all cases there is evidence of clustering, which suggests that a GARCH model might be an appropriate specification to capture the properties of the data. Table 2 reports some descriptive statistics. Bonds issued by municipalities belonging to the states of California and Columbia have positive mean values, whilst those for the states of Colorado and Ohio are negative. All series have standard deviations of a similar size and appear to be negatively skewed.

[Insert Tables 1-2 and Figure 1 about here]

4. Empirical Analysis

4.1. Hypotheses Tested

We test for mean and volatility spillovers by placing restrictions on the relevant parameters; in particular, the following null hypotheses are tested:

Tests of no volatility spillovers and/or contagion (please add note that mean spillovers are also tested)

H_{01}: No volatility spillovers and no contagion from California Municipal Green Bonds to Columbia Municipal Green Bonds: $a_{31} = a_{31}^{*} = g_{31} = g_{31}^{*} = 0$. The null hypothesis is that volatility in the Columbia Municipal Green Bonds is not affected by that in the California Municipal Green Bonds, neither over the full sample period nor during the Covid-19 pandemic and around the COP policy announcements.

H_{02}: No contagion, that is, no shift in the transmission of volatility from the California Municipal Green Bonds to the Columbia Municipal Green Bonds during the Covid-19 pandemic and around the COP policy announcements: $a_{31}^{*} = g_{31}^{*} = 0$.

H_{03}: No volatility spillovers from the California Municipal Green Bonds to the Columbia Municipal Green Bonds over the full sample period: $a_{31} = g_{31} = 0$. This hypothesis complements H_{02}. If one rejects H_{03} and does not reject H_{02}, there is no volatility contagion, only spillovers; if instead one does not reject H_{03} but rejects H_{02}, volatility is transmitted from the California Municipal Green Bonds to the Columbia Municipal Green Bonds only during the Covid-19 pandemic and around the COP policy announcements, which implies “shift contagion.”

We test the same hypotheses for spillovers from the Colorado Municipal Green Bonds to the Columbia Municipal Green Bonds and the Ohio Municipal Green Bonds as well as all possible cross-variables spillover/contagion effects**.** Overall we test nine sets of null hypotheses.

Finally, we compute conditional correlations between municipal bonds issued by the states of California and Colorado as $\rho_{12,t} = h_{12,t}/(\sqrt{h_{11,t}}\sqrt{h_{22,t}})$, Colorado and Columbia as $\rho_{23,t} = h_{23,t}/(\sqrt{h_{22,t}}\sqrt{h_{33,t}}$, Columbia and Ohio as $\rho_{34,t} = h_{34,t}/(\sqrt{h_{33,t}}\sqrt{h_{44,t}}$, California and Columbia as $\rho_{13,t} = h_{13,t}/(\sqrt{h_{11,t}}\sqrt{h_{33,t}})$, California and Ohio as $\rho_{14,t} = h_{14,t}/(\sqrt{h_{11,t}}\sqrt{h_{44,t}})$, and Colorado and Ohio as $\rho_{24,t} = h_{24,t}/(\sqrt{h_{22,t}}\sqrt{h_{44,t}}$, respectively.

4.2. Discussion of the Results

In order to test the adequacy of the models, Ljung–Box portmanteau tests were performed on the standardized and standardized squared residuals. Overall, the results indicate that the selected VAR-GARCH(1,1) specification captures satisfactorily the persistence in the volatility of municipal green bonds in all estimated models. There is no evidence of causality effects in the conditional mean, whereas these appear to be present in the conditional variance. Note that the sign of the coefficients on cross-market volatilities cannot be determined. Point estimates of the VAR-GARCH(1,1) model parameters for the conditional mean equation and conditional variance equation, as well as the associated robust standard errors and likelihood function values, are presented in Tables 3 and 4, respectively. We select the optimal lag length of the mean equation using the Schwarz information criterion.

Mean and volatility spillovers are tested by placing restrictions on the relevant parameters as discussed in Section 4.1. The results suggest that there are very limited dynamic linkages between the first moments compared to the second moments. In particular, we find positive and significant causality running from the California to the Colorado bonds ($\beta_{21} = 0.014$) only at the standard 5% significance level. Neither the Covid-19 pandemic nor the COP policy announcements appear to have had any influence on the causality-in-mean dynamics. The exogenous variable in the conditional equation, which is a proxy for monetary policy, has a negative and significant effect.

Causality effects in the conditional variance vary in magnitude across green bonds (note that the signs on cross-market volatilities cannot be determined). The following points are noteworthy. When neither the Covid-19 period nor the COP policy announcements are taken into account (basic model), evidence of causality-in-variance is detected, at the standard 5% significance level, with volatility spillovers running from bonds issued in California to those issued in Columbia (a_{21} = -0.151), Colorado (a_{31} = 0.048) and Ohio (a_{41} = 0.049), and also from Colorado to Columbia (a_{32} = 0.015) and Ohio (a_{42} = 0.018).

[Insert Tables 3-4 and Figure 2 about here]

Next, we considered the possible impact of the exogenous shock represented by the Covid-19 pandemic and of the policy announcements made at the COP meetings by including in the model suitably defined switch dummies (see footnote 3). The former caused severe disruption to the world economy and to global supply chains through the restrictions on mobility imposed by national governments, and it was a combination of supply and demand shocks which spread from the real to the banking and financial sectors. As for the COP meetings, these were the result of years of diplomatic efforts finally leading in June 1992 to the establishment of the UN Framework Convention on Climate Change (UNFCCC), with the governments of the signatory countries becoming parties to this legally binding convention and then meeting regularly at the so-called Conferences of Parties (COPs). At these meetings various policies have been agreed over the years to combat climate change by reducing global warming through a reduction in gas emissions and by setting targets to limit the rise in average temperature. One of the most successful recent meetings took place in Glasgow, UK, 30 November – 12 December 2021 (see footnote 3 for the venues and dates of the other meetings during the period of interest). In particular, at that time all countries were asked to strengthen their 2030 targets by the end of 2022 to align them with the Paris Agreement's temperature goals, and also to submit long-term strategies aiming to reach net-zero emissions by 2050.

The evidence based on the switch dummies implies that the Covid-19 pandemic affected the causality-in-variance dynamics. In particular, during the crisis, stronger volatility spillovers can be found running from the green bonds issued in California to those issued in Columbia ($a_{21} + a_{21}^{*}$ = -0.196), Colorado ($a_{31} + a_{31}^{*}$ = 0.149) and Ohio ($a_{41} + a_{41}^{*}$ = 0.132), and also from

Colorado to Columbia ($a_{32} + a_{32}^{*} = 0.023$) and to Ohio ($a_{42} + a_{42}^{*} = -0.026$); the strongest volatility spillovers run from California to Colorado. By contrast, the COP policy announcements do not appear to have had any effect on the dynamic linkages between the second moments. [4]

To sum up, our results indicate that there are no significant causality-in-mean effects at the standard 5% significance level but in one case whilst there is evidence of linkages between the second moments. The implication of these findings is that the Covid-19 pandemic played an important role in shaping the dynamic linkages between the selected set of bonds considered in our analysis, mostly between their volatilities. The municipal green bonds issued in California clearly stand out as the dominant ones.

Finally, there is evidence of co-movement between green municipal bonds, as shown by the conditional correlations obtained from the VAR-GARCH(1,1) model (Figure 2). In particular, the conditional correlations between the four bonds under examination are generally positive. It is also noteworthy that there has been a downward shift in pairwise correlations during the Covid-19 pandemic, whereas those for the periods around the COP policy announcements are unchanged. This is not surprising given the fact that the shift dummies corresponding to the latter events had been found to be insignificant.

From the point of view of financial integration, both the smaller (in absolute value) spillover coefficients and the lower correlations imply that the financial markets in question were less tightly linked during the Covid-19 pandemic period when integration appears to have decreased as a result of this exogenous shock (and thus greater portfolio diversification opportunities became available), though it is plausible to expect that this effect will only be temporary as in the case of other economic and financial variables.

5. Conclusions

The objective of this study is to shed new light on the dynamic linkages (interdependence) between the municipal green bonds issued in four US states, and on whether shifts in their spillover parameters (contagion) are associated with the Covid-19 pandemic and

[4] We also examined the possible impact of the Russia-Ukraine war by including in the model a switch dummy defined as being equal to 0 until 24 February 2024 and to 1 afterwards, but this regressor turned out to be insignificant, which implies that the conflict in question, despite leading to an energy crisis, did not directly affect the linkages between the municipal green bonds being considered.

the COP policy announcements (contagion), the latter issue not having been previously investigated in the rapidly growing literature on green bonds. Specifically, four-variate VAR-GARCH (1,1) models for green bonds, issued by municipalities in California, Colorado, Columbia and Ohio, and their volatilities are estimated, and tests are carried out for the presence of spillovers (interdependence), as well as for possible shifts in the spillover parameters; tests for the statistical significance of appropriately defined dummies for the Covid-19 pandemic and the COP policy announcements respectively are performed in the latter case. Conditional correlations are also calculated for the series of interest. The focus on examining interactions in the municipal green bond market, the adoption of a framework to model simultaneously linkages between returns and their volatilities, and the investigation of possible parameter shifts affecting the degree of financial integration are all novel contributions to this area of the literature.

Our results provide a number of interesting insights. In particular, they suggest that the Covid-19 pandemic influenced the dynamics of the conditional variances (i.e., there was contagion), with the spillover parameters shifting during the pandemic, whilst the COP policy announcements had no effects. The combined evidence from the estimated models and the conditional correlations implies weaker linkages, and thus a lower degree of financial integration (and greater portfolio diversification opportunities), during the Covid-19 period; however, the impact of this exogenous shock is likely to disappear over time following the phasing out of the Covid-19 restrictions and the rapidly diminishing disruption to global supply chains and other economic and financial variables.

Future research will use a wider set of green municipal bonds to analyse their linkages with green stocks and other financial instruments; this type of analysis will provide more extensive information bout the suitability of these green financial instruments for portfolio diversification purposes.

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Table 1. Data description

Municipal Bonds	Issuers	Fitch Rating
California	California Infrastructure Authority (Clean Water Fund Bonds)	AAA
Colorado	Lower Colorado River Authority	A+
Columbia (DC)	District of Columbia Water & Sewer Authority	AA
Ohio	American Municipal Power – Ohio	A-
Interest Rate	3-month Treasury Bills	

Notes: Data are sourced by Bloomberg. The sample period goes from 2/1/2015 to 2/2/2023, for a total of 2110 observations.

Table 2. Descriptive Statistics

Variables	Mean	S.D.	Skewness	Kurtosis	Min	Max	Obs.
California	0.002	1.297	-0.341	12.37	-11.25	8.08	2110
Colorado	-0.001	0.713	0.001	8.71	-4.58	5.33	2110
Columbia	0.001	0.283	-0.678	21.29	-2.52	2.14	2110
Ohio	-0.004	0.194	-0.125	19.12	-1.84	1.84	2110

Notes: S.D. stands for standard deviation.

Table 3. Multivariate GARCH(1,1) Parameters Estimates

Conditional Mean Equation							
Basic Model				**COVID-19 Pandemic**		**COP Announcements**	
α_1	**0.005**	(0.002)					
α_2	-0.001	(0.000)					
α_3	0.001	(0.050)					
α_4	**-0.008**	(0.022)					
β_{11}	**0.022**	(0.005)					
β_{12}	0.012	(0.443)	β_{12}^*	0.016	(0.033)	0.011	(0.073)
β_{13}	-0.014	(0.571)	β_{13}^*	0.073	(0.056)	-0.068	(0.017)
β_{14}	0.023	(0.651)	β_{13}^*	-0.011	(0.088)	0.033	(0.045)
β_{22}	**0.025**	(0.012)					
β_{21}	**0.014**	(0.005)	β_{21}^*	0.021	(0.097)	-0.023	(0.123)
β_{23}	0.017	(0.011)	β_{23}^*	0.081	(0.089)	0.068	(0.042)
β_{24}	0.027	(0.062)	β_{24}^*	0.021	(0.018)	-0.028	(0.071)
β_{33}	0.037	(0.065)					
β_{31}	0.012	(0.443)	β_{31}^*	0.034	(0.101)	0.011	(0.135)
β_{32}	-0.012	(0.571)	β_{32}^*	-0.093	(0.078)	-0.031	(0.057)
β_{34}	0.043	(0.651)	β_{34}^*	0.071	(0.115)	0.047	(0.042)
β_{44}	**0.087**	(0.026)					
β_{41}	0.004	(0.018)	β_{41}^*	0.011	(0.119)	0.001	(0.114)
β_{42}	0.106	(0.036)	β_{42}^*	-0.056	(0.015)	0.071	(0.079)
β_{43}	0.025	(0.009)	β_{43}^*	-0.041	(0.034)	-0.102	(0.064)
3-month T-Bill	**-0.043**	(0.022)					
Log-Lik	3256.12			3331.7 2		3298.31	
$LB_{10\ (California)}$	4.565			4.221		4.324	
$LB2_{10\ (California)}$	4.108			4.311		4.287	
$LB_{10\ (Colorado)}$	3.086			2.534		2.651	
$LB2_{10\ (Colorado)}$	3.001			3.089		3.201	
$LB_{10\ (Columbia)}$	3.443			3.801		3.901	
$LB2_{10\ (Columbia)}$	4.061			3.773		3.744	
$LB_{10\ (Ohio)}$	3.852			3.991		3.664	
$LB2_{10\ (Ohio)}$	3.778			4.113		4.101	

Notes: P-values are calculated using the quasi-maximum likelihood method of Bollerslev and Wooldridge (1992), which is robust to the distribution of the underlying residuals. Standard errors are reported in brackets. Estimates in bold denote rejection at the 5% levels. Point estimates reported in the second column, headed Basic Model, refer to the restricted model where neither the COVID-19 pandemic nor the COP announcements were taken into account and therefore shift dummies are not included. In the other columns only cross currencies shift parameters, with dummies associated to the COVID-19 pandemic or the COP announcements, are reported. $LB_{10(.)}$ and $LB2_{10(.)}$ are the Ljung–Box test (1978) of significance of no autocorrelations of 10 lags in the standardized and standardized squared residuals, respectively. The parameter β_{21} measures the causality effect of Colorado on California returns, whereas a_{21} measures the causality-in-variance effect of Colorado returns volatility on California returns volatility. The effect of the COVID-19 pandemic or the COP announcements on California returns is measured, in turn, by ($\beta_{21} + \beta_{21}^*$) whereas ($a_{21}+a_{21}^*$) captures the effects on conditional volatility. The covariance stationarity condition is satisfied by all the estimated models, all the eigenvalues of $A\otimes A + G\otimes G$ being less than one in modulus. Note that in the conditional variance equation the sign of the parameters cannot be determined.

Table 4. Multivariate GARCH(1,1) Parameters Estimates

Conditional Variance Equation							
Basic Model				**COVID-19 Pandemic**		**COP Announcements**	
c_{11}	**0.065**	(0.014)					
c_{22}	**0.059**	(0.011)					
c_{33}	**0.033**	(0.015)					
c_{44}	**0.015**	(0.004)					
a_{11}	**0.233**	(0.028)					
a_{12}	0.002	(0.005)	a_{12}^*	0.001	(0.001)	0.002	(0.088)
a_{13}	0.064	(0.551)	a_{13}^*	0.125	(0.987)	0.201	(0.401)
a_{14}	0.057	(0.104)	a_{14}^*	0.005	(0.554)	0.087	(0.111)
a_{22}	**0.324**	(0.037)					
a_{21}	**-0.151**	(0.054)	a_{21}^*	**-0.045**	(0.001)	0.077	(0.099)
a_{23}	0.056	(0.088)	a_{23}^*	0.113	(0.224)	0.045	(0.302)
a_{24}	0.053	(0.097)	a_{24}^*	0.097	(0.445)	0.111	(0.409)
a_{33}	**0.221**	(0.022)					
a_{31}	**0.048**	(0.016)	a_{31}^*	**0.101**	(0.045)	0.001	(0.022)
a_{32}	**0.015**	(0.006)	a_{32}^*	**0.008**	(0.001)	0.099	(0.077)
a_{34}	0.039	(0.095)	a_{34}^*	0.065	(0.111)	0.006	(0.146)
a_{44}	**0.271**	(0.071)					
a_{41}	**0.049**	(0.019)	a_{41}^*	**0.083**	(0.022)	-0.077	(0.234)
a_{42}	**0.018**	(0.021)	a_{42}^*	**-0.044**	(0.021)	0.032	(0.101)
a_{43}	0.006	(0.228)	a_{43}^*	0.003	(0.087)	0.098	(0.276)
g_{11}	**0.957**	(0.007)					
g_{12}	-0.001	(0.002)	g_{12}^*	0.021	(0.099)	0.001	(0.002)
g_{13}	0.592	(0.412)	g_{13}^*	0.001	(0.001)	0.034	(0.099)
g_{14}	0.526	(0.654)	g_{14}^*	0.004	(0.007)	0.002	(0.109)
g_{22}	**0.912**	(0.022)					
g_{21}	**0.065**	(0.032)	g_{21}^*	**0.022**	(0.001)	-0.067	(0.189)
g_{23}	0.521	(0.442)	g_{23}^*	0.098	(0.144)	0.045	(0.331)
g_{24}	0.346	(0.201)	g_{24}^*	0.021	(0.066)	-0.003	(0.005)
g_{33}	**0.976**	(0.004)					
g_{31}	**0.553**	(0.169)	g_{31}^*	**0.231**	(0.089)	0.052	(0.066)
g_{32}	0.061	(0.553)	g_{32}^*	**0.012**	(0.002)	-0.002	(0.009)
g_{34}	0.521	(0.673)	g_{34}^*	0.108	(0.223)	0.252	(0.333)
g_{44}	**0.952**	(0.019)					
g_{41}	0.284	(0.318)	g_{41}^*	**0.045**	(0.015)	0.016	(0.075)
g_{42}	**0.054**	(0.006)	g_{42}^*	**0.093**	(0.042)	0.021	(0.163)
g_{43}	0.341	(0.228)	g_{43}^*	0.204	(0.301)	-0.302	(0.555)

Note: See notes Table 3.

Figure 1. Municipal Green Bonds Returns

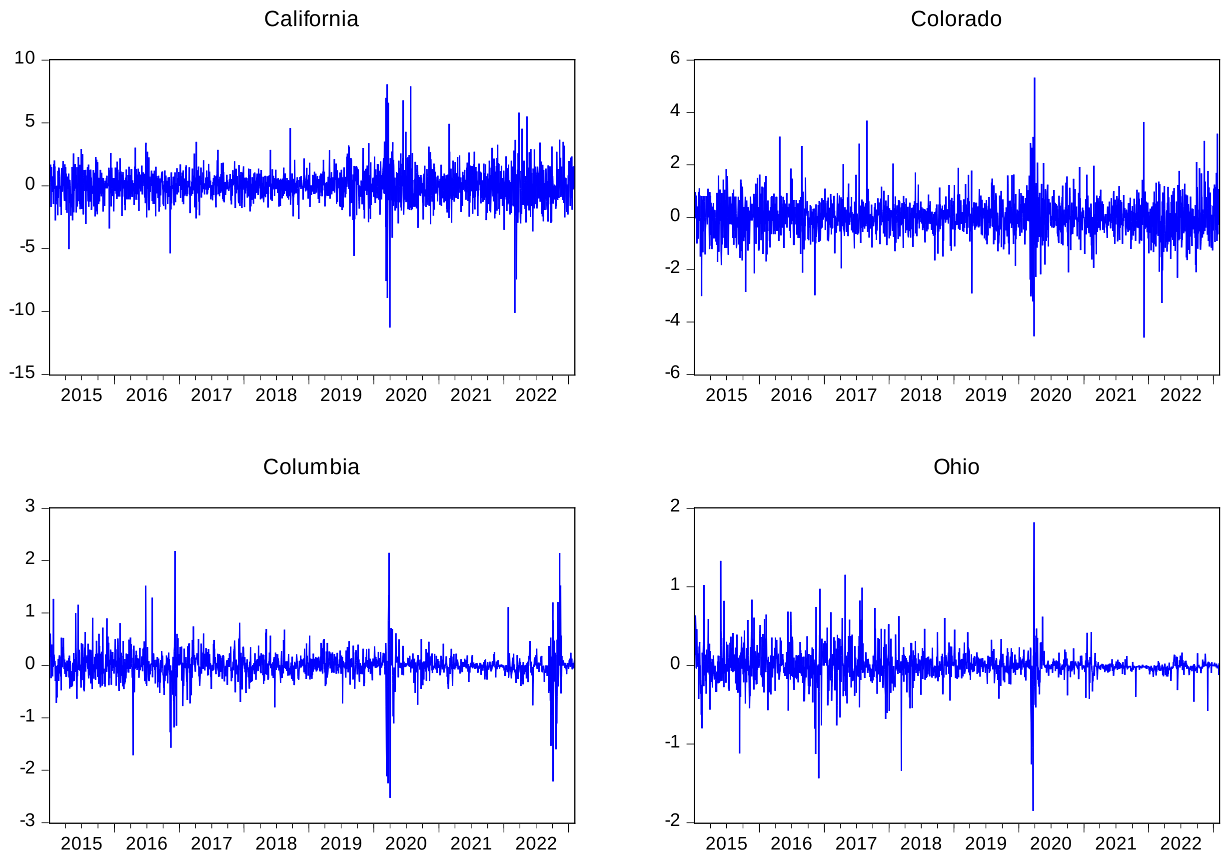

Figure 2. Conditional Correlations