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QUANTILE DEPENDENCE BETWEEN GREEN BONDS, STOCKS, BITCOIN, COMMODITIES AND CLEAN ENERGY

Abstract. *The development of the green bond market has been magnificent recently, but it is necessary to be accelerated for financial sustainability over the globe. In response to increasing interest in the time-varying nexus between green bonds and other assets, the current study empirically investigates the asymmetric relationship between green bonds and other conventional assets, including Bitcoin price, S&P 500, Clean Energy Index, GSCI Commodity Index, and CBOE volatility using recently proposed and novel methods of quantile on quantile regression and Granger causality in quantiles approaches. Our mainstream results demonstrate that other assets under study strengthen green bonds over sample period studied, and this impact is more pronounced in higher quantiles of respective variables. Moreover, our quantile causality test further confirms these results with robust finding across time scales and quantiles. To enhance clean energy and energy efficiency, policymakers should take into consideration limiting eligibility criteria in policies supporting green bonds or limiting refinancing using green bonds. Stakeholders driving the green bond market should scale up the market to finance the required global investment level.*

Keywords*: Green bonds, equity and other prices, diversification, Quantile on Quantile approach, Granger causality in quantiles*.

JEL Classification: G10, G11, G15

1. Introduction

The European Investment Bank introduced the first green bonds in 2007 as a novel instrument corresponding to the recent environment crisis (Sadkowska et al. 2020). This financial asset has been attracted by both market participants and academic attention (Huynh, 2020a). As per Tu et al. (2020), green bonds are newly developed financial instruments for funding environmental projects and social welfare through a low-carbon financing framework. Low-carbon finance is a kind of economic policy, system, technology, and goods and services designed to develop a low-carbon economy further. Like traditional fixed income securities, companies can issue green bonds to raise capital to finance their significant investment.

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Nonetheless, green bonds are intended to positively benefit environmental benefits like lessening carbon emissions and reducing pollution (Tang and Zhang, 2020). The international market for green bonds has increasingly developed since the World Bank issued in 2008. Many nations and organizations have carried out divergent definitions and criteria for this financial product without an internationally recognized standard Li et al. (2020). Since then, the global green bond market has increasingly developed, the market attracted approximately 11 billion USD in 2013 and 36 billion USD in 2014 to 167 billion USD in 2018 (Maltais and Nykvist, 2020; Huynh, 2020a; Hung, 2021). As a result, the green bond market is small but developing quickly and becoming more popular in the global financial market. Yet, in spite of rapid growth, there has to date been very little academic studies on green bonds (Maltais and Nykvist, 2020). This product is expected to thrive by attracting the particular interest of multiple issuers and a wide range of ethical investors, including mutual funds, pension funds, insurance firms. More importantly, stock exchanges, such as London, Mexico, Sweden, Oslo, Luxembourg, and Shanghai, have constructed specific green bond market segments to enhance this market (Reboredo, 2018). Figure 1 shows the quick development of the green bond market in Sweden since 2015.

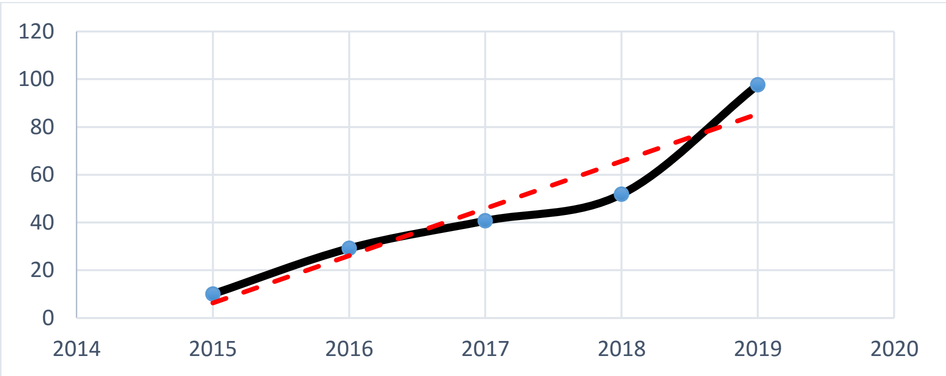

Figure 1. Green Bonds issued in Sweden (million SEK).

Understanding the interrelatedness between green bond and other financial markets are significant for investors since it may shed light on the diversification benefits of the allocation of green bonds to a portfolio and illustrate the influence of green bond prices on price variations in the financial markets. Not surprisingly, the research of those impacts is also particularly relevant to strengthening environmentally friendly portfolios and creating an incentive scheme to mobilize the necessary financial resources to foster from traditional economy to climate-resilient economy (Reboredo, 2018; Huynh, 2020a). In addition, an in-depth analysis of the correlation between green bonds and other financial instruments benefits investors since they are interested in environmentally friendly portfolios and want to know the portfolio allocation, which may be given rise to by the nexus between green bonds and other financial asset classes.

As a result, the primary purpose of this paper is to estimate the asymmetric connectedness structure between the green bonds and other asset classes, including Bitcoin price, S&P 500, Clean Energy Index, GSCI Commodity Index, and CBOE volatility, given that investor portfolios are likely to be made up of green bonds and financial assets traded in those markets. The current study characterizes the asymmetric relationship structure between green bonds and other related financial asset classes employing quantile regression analysis, quantile on quantile regression, and quantile Granger causality approaches. We utilize a quantile interval of 0.05 intervals to discover the significant co-movements of this relationship. According to Reboredo (2018), green bond markets have theoretical linkages to other financial assets across the discount rate channel, and empirical issues of the green bond prices react to extreme price allocations in financial markets that need to be studied.

However, only a limited number of prior studies have looked into the interdependence between green bonds and traditional assets (Nguyen et al. 2020). For instance, Reboredo (2018) documents that the green bond market coupled with corporate and treasury bond markets and weakly connects with stock and energy commodity markets. More specifically, he also suggests that green bonds are influenced by substantial price transmissions from corporate and treasury fixed-income markets. Baulkaran (2019) uses a market model to examine the stock market reaction to news announcements of green bonds issuance and provides evidence that green bonds issued with higher coupon rates elicit a negative market reaction. This finding agrees with Wang et al. (2020), Zerbib (2019), Pham and Huynh (2020), Nanayakkara and Colombage (2019).

Recent literature provides mixed and inconclusive results about whether the connectedness between green bonds and other related financial assets is significant or not. Huynh et al. (2020b) consider the specific role of AI and robotics stocks in portfolio diversification and contribute to the research on cryptocurrencies and green financial instruments. They report that Bitcoin, green bonds, and NASDAQ AI are shock senders, which implies that even though these assets can be considered as good investments due to high returns, the high volatility in these asset’s prices fluctuates remarkably. Park et al. (2020) test whether green bonds experience asymmetric volatility and reveal that green bonds have a unique property whose volatility is sensitive to positive innovations, unlike other financial assets. More importantly, they also affirm that the green bond and equity markets have several spillover effects but that neither responds remarkably to other markets' negative innovations. In the same vein, Reboredo and Ugolini (2020) uncover that the green bond market is closely linked to the fixed-income and currency markets, and it receives sizeable price spillovers from those markets and transmits negligible reverse effects. Furthermore, they also reveal that the green bond market is weakly connected with stock, energy, and high-yield corporate bond markets. On the other hand, Liu et al. (2020) determine downside and upside risk spillovers from clean energy to green bond markets and provide evidence that there is a positive dynamic average and tail dependence between green bonds and clean energy stock markets. Hammoudeh et al. (2020) find that the link carbon emission allowances prices causing green bonds is statistically significant, and there is a unidirectional association between clean energy and green bonds. Jin et al. (2020) indicate that the green bond market is the best hedge for carbon futures and performs well even in the crisis period. Similarly, Nguyen et al. (2020) contribute the present literature by investigating the nexus among green bonds and other financial markets, provide evidence that most relationship emerged and reached a peak in the post global financial crisis 2008. This result agrees with the paper of Le et al. (2020), who explore the time and frequency domain relationship and spillover effects among Fintech, green bonds, and cryptocurrencies.

This study analyzes the causal association between green bonds, commodities, and other financial asset classes, considering all quantiles of the distribution by employing the advanced quantile on the quantile framework. We also use Granger causality in quantiles test introduced by Troster et al. (2018) that assesses causal association in all conditional quantiles of the distribution. Using these frameworks' primary motivation is its advanced ability to blend both quantile regression and nonparametric techniques (Hashmi et al. 2020; Troster et al. 2018). As a result, it allows us to estimate the asymmetric effect of quantiles of other assets on quantiles of green bonds, which is impossible under traditional time series econometric methods (Chang et al. 2020; Hung, 2019). In essence, the quantile on quantile regression offers a more detailed estimation of the whole conditional distribution than the conditional mean-regression analysis (Troster et al. 2018), which centers merely on one part of the conditional distribution. Besides, a casual tail association does not imply causality in the mean, whereas a connection with mean-causality shifts at least a non-negligible number of quantiles. Specifically, we estimate a continuum of quantile functions that distinguishes the definition of Granger causality in distribution rather than investigating a necessary condition for Granger causality. Such complicated proposed empirical analysis provides an inclusive methodology with a complete depiction of the cross-dependence between quantiles of other related assets and green bonds.

This study contributes to the prior literature by considering a detailed analysis of the green bond-other financial market relationship. First, concentrating on the nexus between green bonds and other financial markets, the current study provides evidence of using green bonds as a remarkable diversification in the portfolio of stocks and commodities. Second, this study contributes to the methodological application by supplementing the theoretical and policy-level contribution. We employ the quantile on quantile regression proposed by Sim and Zhou (2015) to evaluate the association between variables across quantiles of the variables. Therefore, we can estimate the influence of one variable's entire quantile distribution on the quantile distribution of the other variable. The heterogeneous behavior of green bonds and other assets under study across space and time has significant policy implications. Third, we also employ the Granger causality in quantiles test produced by Troster et al. (2018) that investigates the causal association in all quantiles of the conditional distribution. Under this approach, we are able to identify causality connectedness between green bonds and other financial markets at the lower, median, and upper tails of the distribution. Overall, our empirical estimation supplements past studies mainly on cross-asset nexus and affirms the hedging potential of green bonds for other asset markets.

The rest of the paper is organized as follows. Section 2 represents quantile on quantile and Granger causality in quantiles methodologies and data description. Section 3 reports empirical results and discussion. Section 4 concludes the study with implications.

2. Methodology

In this paper, we utilize the quantile regression analysis (QRA), quantile on quantile regression (QQR) and quantile Granger causality techniques to examine the asymmetric intercorrelation between green bonds and other traditional financial markets. More importantly, the QQR framework combines the characteristics of both non-parametric method and quantile regression (Hashmi, et al. 2020; Owusu Junior and Tweneboah, 2020). It regresses the quantiles of the other asset classes on green bonds to estimate the asymmetric and spatial properties of the model over time (Hashmi, et al. 2020). To supplement the QQR approach, we have also used the quantile Granger causality test proposed by Troster et al. (2018) to identify the asymmetric causal association between variables under consideration over the selected bandwidth parameter h = 0.05. In this section, we briefly note on QQR and Quantile Granger causality approaches.

The QQR approach

In order to bearish connectedness between green bond (GB) markets and financial asset returns (FM), the QQR approach seems appropriate because quantiles can depict asymmetry between high and low returns. Let look at this relationship

$$GB_t = \beta^{\theta}(FM_t) + u_t^{\theta} \quad (1)$$

where GB_t and FM_t denote the green bond and other selected asset classes at period t, θ is the θ^{th} quantile of the conditional distribution of GB_t and u_t^{θ} is the error quantile whose θ^{th} conditional quantile is made-up to be zero, and $\beta^{\theta}(.)$ illustrates slope of this nexus.

One primary drawback of quantile regression framework is that it does not distinguish how varying levels of positive or negative shocks of other financial asset classes impact green bonds. As a result, we have conducted local linear regression to explore the asymmetric effect of other assets on green bonds. We can extend equation (1) by a first order Taylor expansion of a quantile of FM_t as follows:

$$\beta^{\theta}(FM_t) \approx \beta^{\theta}(FM^{\tau}) + \beta^{\theta'}(FM^{\tau})(FM_t - FM^{\tau}) \quad (2)$$

where $\beta^{\theta'}$ represents the partial derivative of $\beta^{\theta}(FM_t)$, indicative of a marginal impact as the slope. It is obvious that θ is the functional form of $\beta^{\theta}(FM^{\tau})$ and $\beta^{\theta'}(FM^{\tau})$ while τ is the functional form of FM and FM^{τ}, therefore θ and τ are functional form of $\beta^{\theta'}(FM^{\tau})$ and $\beta^{\theta}(FM^{\tau})$. If we present $\beta^{\theta}(FM^{\tau})$ and $\beta^{\theta'}(FM^{\tau})$ by $\beta_0(\theta,\tau)$ and $\beta_1(\theta,\tau)$, respectively, then we have

$$\beta^{\theta}(FM_t) \approx \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(FX_t - FM^{\tau}) \quad (3)$$

If we replace Equation (2) into fundamental QQR equation (1), we have

$$GB_t = \underset{*}{\beta_0(\theta,\tau) + \beta_1(\theta,\tau)}(FX_t - FM^{\tau}) + u_t^{\theta} \quad (4)$$

where (*) provides the conditional quantile of θ^{th} of green bond. These equations depict the relationship between the quantiles of green bonds and other financial asset classes. As in ordinary least squares (OLS), a similar minimization is used to arrive at equation (5)

$$\min_{b_0,b_1} \sum_{i=1}^{n} \rho_{\theta}\left[GB_t - b_0 - b_1(FM_t - FM^{\tau})\right]K\left(\frac{F_n(EX_t) - \tau}{h}\right) \quad (5)$$

where $\rho_{\theta}(u)$ is the quantile loss function demonstrating as $\rho_{\theta}(u) = u(\theta - I(u<0))$ and $K(.)$ is the kernel density function and h represents kernel density function bandwidth parameter. Based on past studies like Sim and Zhou (2015) and Hashmi, et al. (2020), we chose $h = 0.05$ bandwidth of density function for optimal parameters of QQR framework.

Quantile Granger causality approach

Following the paper of Hashmi, et al. (2020), quantile Granger causality carries out as follows

$$H_0^{FM \to GB} : F_{GB}\left(x \mid M_i^{FM}, M_i^{GB}\right) = F_{GB}\left(x \mid M_i^{GB}\right), \text{ for all } x \in R \quad (6)$$

where H_0 in equation (6) is the null hypothesis of Granger non-causality from FM_t to GB_t, $F_{GB}\left(. \mid M_i^{FM}, M_i^{GB}\right)$ is the conditional scattering function of GB_t given $\left(M_i^{FM}, M_i^{GB}\right)$.

Following the study of Troster et al. (2018), we employ the D_T test to take into account the null hypothesis in equation (6) by determining the quantile autoregression framework (QAR) $m(.)$ for entire $\pi \in \Gamma \subset [0,1]$. The null hypothesis of non-Granger causal nexus as follows:

$$QAR(1): m^1\left(M_i^{GB}, \partial(\pi)\right) = \lambda_1(\pi) + \lambda_2(\pi)GB_{i-1} + \mu_t\Omega_Y^{-1}(\pi) \quad (7)$$

Supreme probability technique is employed by the QAR in an identical space of grid of quantiles, and $\Omega_Y^{-1}(.)$ presents the converse of a conventional ordinary scattering function. We compute the quantile autoregressive frameworks in equation (7) with lagged variable to another variable, the QAR approach with the help of equation (7) can be written as follows:

$$Q_\pi^{GB}\left(GB_i \mid M_i^{GB}, M_i^{FM}\right) = \lambda_1(\pi) + \lambda_2(\pi)GB_{i-1} + \eta(\pi)FM_{i-1} + \mu_i\Omega_\gamma^{-1}(\pi) \quad (8)$$

Data

In this paper, we look into the asymmetric relationship between green bonds and financial asset classes. The period chosen for this study covers from April 2013 to December 2019, which allows for a better understanding of the time-varying connectedness between green bonds and other assets as well as data availability of Bitcoin. It contains the time series of the S&P Green Bond index (GB), Bitcoin price (BIT), S&P 500 (SP), Clean Energy Index (CEI), GSCI Commodity Index (CI), and CBOE volatility (VIX). Our daily data are obtained from the DataStream database, and daily log-returns of price series are employed in estimation.

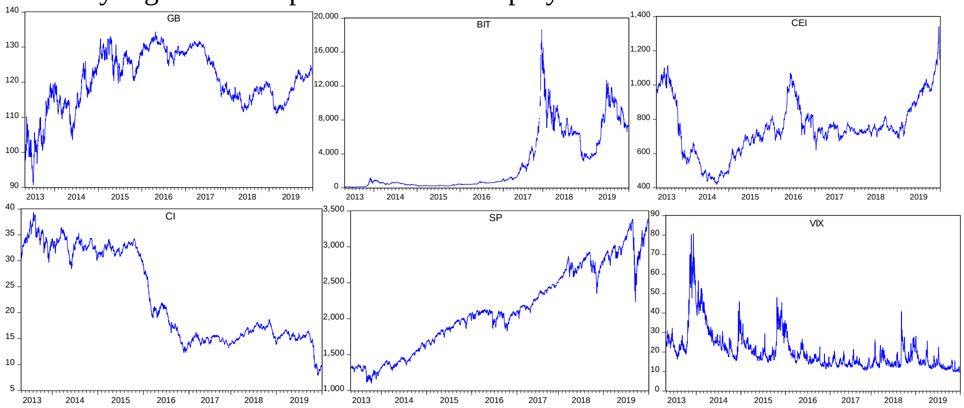

Figure 2. Price dynamics of green bonds and other assets

Table 1. Descriptive statistics

	GB	BIT	CEI	CI	S&P 500	VIX
Mean	0.008692	0.165077	0.006989	-0.046126	0.039829	-0.036738
Max	6.815362	36.14002	5.835404	6.557619	8.968316	40.54651
Min	-3.782315	-33.11594	-8.111435	-12.87549	-12.76521	-35.05885
Std. Dev	0.665330	4.424622	1.231096	1.295592	1.104545	7.328305
Skewness	0.711042	-0.188299	-0.293656	-0.861092	-0.938241	0.679571
Kurtosis	13.01748	12.85781	6.273927	11.49696	21.63060	6.556321
Jarque-Bera	10254.28***	9748.037***	1108.198***	7528.949***	35120.48***	1451.885***
ADF	-51.76445***	-49.74714***	-41.71054***	-49.91165***	-18.30982***	-53.38337***
ARCH	99.20172***	142.7549***	132.8485***	91.92062***	570.4455***	112.6281***
Observations	2404	2404	2404	2404	2404	2404

Notes: *** represents rejection of null hypotheses at 1% level of significance.

Table 1 shows the descriptive statistics for green bonds and five equity indices under consideration. We can observe that Bitcoin has the highest mean (0.16%), followed by the S&P 500. Specifically, VIX is most risky with a standard deviation of 7.32%, whereas green bond is the least risky market with a standard deviation of 0.66%. As indicated in Table 1, our data do not have a normal distribution with respect to the Jarque-Bera test. Similarly, the augmented Dickey-Fuller (ADF) test demonstrates that all variables are stationary at level. Furthermore, based on the ARCH effects, we can reject the null hypothesis of no ARCH effects. As a result, all considered series are appropriate for further statistical analysis. Figure 2 depicts the dynamics of the daily prices of green bonds and five equity indices over the sample period.
Next, we take into account the unconditional correlation between green bonds and five equity indices by utilizing the correlation matrix. As shown in Figure 3, the nexus between GB and other equities is quite weak based on the Pearson methodology. One robust explanation for this relationship is that investors tend to reallocate their assets among green bonds and other assets (Huynh, 2020c). Figure 4 provides us further insight into the data distribution and correlation structure in terms of the data distribution together with the pairwise correlations between the examined variables.

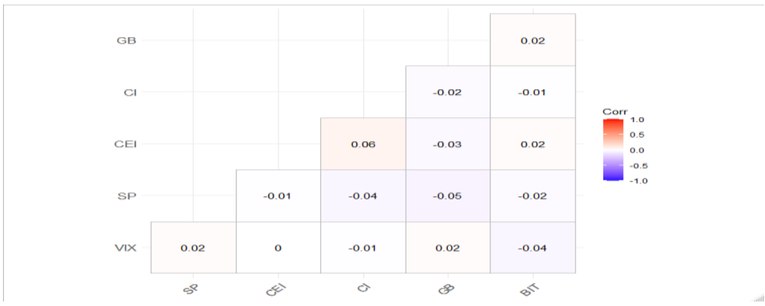

Figure 3. Pair-wise correlations of green bonds and other assets

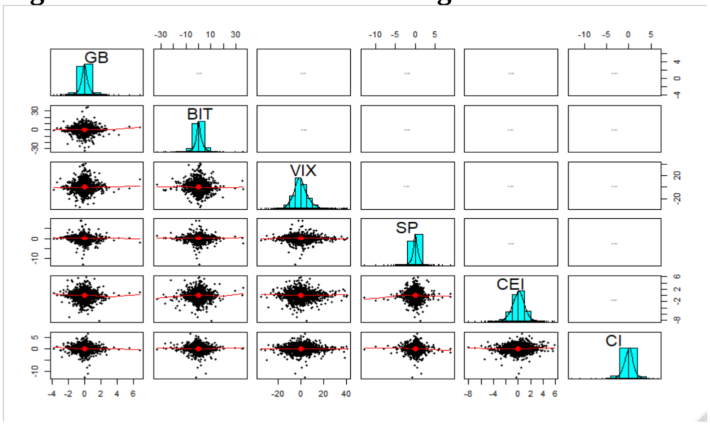

Figure 4. The data distribution and correlation structure of GB and other asset's returns

3. Empirical results

QRA results

Table 2 reports the QRA estimates of green bonds on other indices for the respective markets in terms of the divergence of coefficients obtained from various quantile functions. For the pairs of green bonds with GSCI Commodity Index and VIX, we find negative, highly significant relationships at all quantiles. The long term shows the strongest connectedness. The dependence between GB and CI is significant at lower (0.1 and 0.35) quantiles and higher (0.75 and 0.80) quantiles. On the other hand, in the case of GB-VIX, the negative association is quite significant across all quantiles, leaving aside extreme lower (0.1) and extreme higher (0.9) quantile.

GB-BIT pair witnesses positive relationships in both short and medium terms across all quantiles but inverse in the long run. The magnitude in the latter is quite similar to the short run. In the same vein, the Clean Energy Index's impact on green bonds markets is much more significant at higher quantiles than lower ones that the quantile 0.05 through to 0.60 quantiles demonstrate negative connection and positive beyond that. GB-S&P500 pair has a bit of a different story. The significant influence of S&P 500 stock price on green bond markets can be experienced at medium quantiles as compared to extreme lower and higher quantiles. More specifically, there is an increasingly positive relationship in the short and medium terms, strongest than all other pairs in the long run, and switch from positive nexus to negative at the upper tail from 0.80.

Overall, the QRA results illustrate that the impact of examined variables on green bonds markets increases as quantiles increase. In fact, in higher quantiles, the model fits much better, suggesting that the influence of considered equity indices on green bonds markets is more robust in the long-term horizon but weaker in the short run. Our estimation helps break down the price change structure between green bonds and other markets under study. The increase in conventional financial assets is one robust reason for the variations in the green bond indices. In addition, in terms of the asymmetric nature of the interconnectedness between green bonds and examined variables at different quantiles, our results support the paper of Dawar et al. (2021). More importantly, the inverse associations found in our study would resonate with the portfolio balance and portfolio rebalance theories, in which investors can use green bonds as a vehicle to invest in bond markets linked to conventional financial asset classes (Huynh, 2020c).

The QQR results

The interconnectedness shown by QQR from those of QRA would be inferred once the former can be validated. It is obvious that the statistical significance of coefficients is not available because the QQR is a non-parametric model. Nevertheless, the QQR techniques decompose the QRA results into the specific quantiles of the indicator variables (Owusu Junior and Tweneboah, 2020). As a result, we can endorse the QQR results rely on how closely its coefficients match those of QRA. Table 3 reports the QQR estimates across quantiles. In comparison with QRA estimates that the magnitudes of QQR estimates are greater. Additionally, QQR estimates also have more positive, with more fluctuation through quantiles and time scales. Therefore, we can conclude that the QQR is a significant approach to measure the dynamic asymmetric relationships between green bonds and other examined markets and indicates the pattern in those associations.

Table 2. QRA estimates of green bond and other assets

Quantile	GB-BIT	GB-CEI	GB-CI	GB-S&P 500	GB-VIX
0.05	0.029444**	-0.1321	-0.14048	0.14394	-0.15876**
0.10	0.025307**	-0.12573*	-0.12161**	0.116369	-0.09523
0.15	0.022195*	-0.06406	-0.10789	0.104116*	-0.0428***
0.20	0.013892	-0.04537	-0.08891	0.08067**	-0.02709***
0.25	0.007604	-0.03596	-0.06037	0.053745**	-0.03354***
0.30	0.003693	-0.01802**	-0.04981	0.04511**	-0.03444
0.35	-0.00319**	0.005227	-0.04603**	0.043186*	-0.03309
0.40	-0.01054***	0.007237	-0.04108	0.035822	-0.03726*
0.45	-0.01321***	0.022077*	-0.033	0.035765***	-0.03209
0.50	-0.01584***	0.01647***	-0.0201	0.022927***	-0.02902
0.55	-0.01739	0.000538***	-0.00583	-0.00119	-0.0298
0.60	-0.01763	-.00043	-0.00749**	-0.01383	-0.04013*
0.65	-0.01755***	0.021111	-0.02134	-0.02958*	-0.04264**
0.70	-0.0184	0.04457	-0.02236	-0.03833**	-0.04251***
0.75	-0.01979***	0.047866*	-0.01788***	-0.04176*	-0.03117***
0.80	-0.02007***	0.037385**	-0.01712**	-0.02074**	-0.03091***
0.85	-0.0206***	0.036589***	-0.01718	0.02018	-0.02133***
0.90	-0.02135***	0.023107***	-0.00836***	0.00213***	-0.01174***
0.95	-0.01593***	0.017592**	0.000258	-0.01545	-0.00405***

Notes: ***, **, * indicate statistical significance at 1%, 5% and 10% level, respectively.

Next, we present the main empirical results of the QQR estimates between green bonds and other asset returns under consideration. Figure 5 shows the QQR in three dimensions based on the slope of coefficient $\beta_1(\theta,\tau)$, which explores the impact of the τ^{th} quantile of conventional asset classes on the θ^{th} quantile of green bond markets at various values of θ and τ (the slope coefficient $\beta_1(\theta,\tau)$ in the z-axis against the quantile of the green bonds (θ) in the x-axis and the quantile of other examined variables (τ) in the y-axis).

The results suggest that the impact of conventional assets on green bonds is statistically significant in all cases. More specifically, the influence is more perceptible at the high quantiles of both variables indicating that the increase in traditional asset prices also increases the green bond prices. For the pair of GB-BIT, the effect of BIT on GB is strong and positive, which is discovered in the region corresponding to all quantiles of BIT (0.2-0.9). This outcome is consistent with the study of Le et al. (2020) that green bond prices are a transmitter of volatility from Bitcoin in the total connectedness.

Table 3. QQA estimates of green bond and other assets

Quantile	GB-BIT	GB-CEI	GB-CI	GB-S&P 500	GB-VIX
0.05	2.246177	-0.414	-1.81234	1.034396	-1.13778
0.10	2.106722	-0.10972	-2.01128	1.032158	-1.1481
0.15	2.569843	0.214453	-1.94301	1.21838	-0.99051
0.20	2.898626	-0.11414	-1.8619	1.366186	-0.94321
0.25	3.604771	-0.39334	-1.77939	1.29185	-0.89835
0.30	4.178903	-0.74703	-1.64425	1.119518	-0.79916
0.35	4.41985	-0.8247	-1.59619	0.864252	-0.71401
0.40	3.32691	-0.81518	-1.29623	0.463364	-0.61248
0.45	2.947828	-0.80522	-1.08393	0.574918	-0.50402
0.50	1.925331	-0.79624	-0.96292	0.328277	-0.49003
0.55	1.52821	-0.7572	-1.1378	0.338888	-0.52197
0.60	1.732518	-0.74463	-1.60418	0.418327	-0.47156
0.65	1.830725	-0.71973	-1.34681	0.355832	-0.48831
0.70	2.194978	-0.65546	-1.08306	0.222206	-0.57151
0.75	2.224319	-0.62593	-0.7892	0.371679	-0.56092
0.80	2.496617	-0.77741	-0.59525	0.420732	-0.56224
0.85	2.5624	-0.69078	-0.48423	0.476286	-0.69937
0.90	3.378079	-0.33328	-0.4109	0.602148	-0.81904
0.95	3.945082	-0.26456	-0.37958	0.324322	-0.60165

In the GB and CEI case, the findings show that the CEI index effect is strongly negative on green bond markets over the period studied. The nexus of CEI with GB is noteworthy for a different quantile combination, indicating that CEI negatively impacts GB in the lower to middle quantiles of CEI. Nevertheless, at the higher quantiles of GB and CEI, this negative effect gets weaker. In general, we can conclude that even within the negative impact, GB and CEI's nexus magnitude tends to co-vary. The scenario for the pair of GB-CI is similar to that of GB-CEI. The effect of CI on GB demonstrates an increasing trend along the quantiles, which signifies the negative GB externality generated by the CI. This increase in the demand for innovative green bonds is described in the increasing influence of CI on GB. These findings complement some of the findings by Nguyen et al. (2020).

Similarly, the patterns of GB-VIX is also not entirely different, where extreme higher quantiles (0.8-.095) represent the positive impact of VIX on GB, but this impact turns weak across lower quantiles of GB. On the other hand, during the earlier phase of GB, the strong negative impact of VIX on GB across all quantiles has been observed for the lowest quantiles of GB. VIX has a relatively weak positive effect on GB for the middle quantiles across all quantiles of GB. Unlike other cases above, the graphical depiction of GB-S&P 500 shows a strong positive influence of S&P 500 on GB from lower to higher quantiles of GB. However, this high positive effect persists only for medium to high quantiles of the S&P 500, after which it becomes less pronounced. Our findings are congruent to those of Reboredo (2018), Reboredo and Ugolini (2020), Hammoudeh et al. (2020), these studies empirically verify the green bond-financial asset relationship.

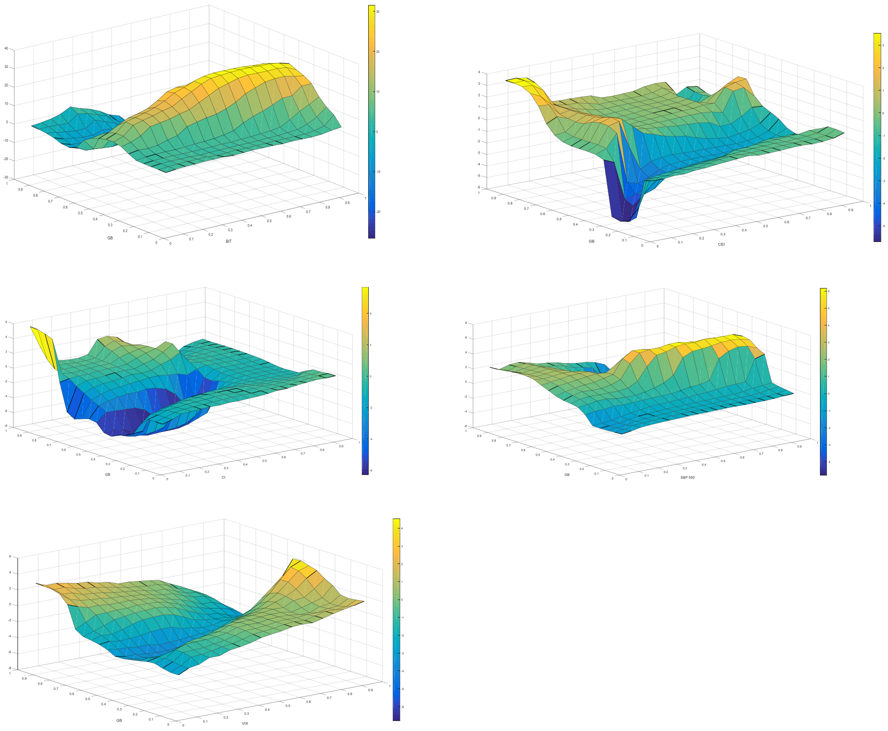

Figure 5. QQR coefficient plots of green bonds and other markets

Results of Granger Causality in quantiles

We also employ Granger causality to confirm the previous results of QQR and verify the primarily bidirectional causal association between green bonds markets and other asset classes under consideration in most of the lower, middle, and upper quantiles in all pairs except the cases of VIX-GB and S&P 500-GB, which fails to represent several significant casual relationships. As shown in Table 4, we are able to explain for such insignificant findings is somewhat less fluctuation in S&P 500 and VIX as described in Figure 5, whereas other markets have comparatively presented much greater fluctuations through time, and their causal association between green bonds and other examined assets substantially changes in different quantiles. Apparently, variation in VIX and S&P 500 does not Granger-cause green bonds at the 5% level of significance based on the significant values. Hence, a unidirectional relationship between GB, VIX, and S&P 500 has been observed in extremely low, middle, and high quantiles of data distribution. Overall, the findings of Granger causality in quantiles affirm that a bidirectional causal association between green bond markets and other financial asset classes has been observed in various quantiles, which supports the previous results of QQR estimates. These results highlight green bonds and other conventional financial markets are strongly connected, and any financial policy designed to establish and carry out financial markets may influence the green bond markets. The bilateral feedback connection between green bonds and other financial assets confirms some past studies (Le et al. 2020; Nguyen et al. 2020; Reboredo, 2018; Liu et al. 2020, Troster et al. 2018).

Table 4. Granger Causality in quantiles

Quantiles	$GB \rightarrow BIT$	$BIT \rightarrow GB$	$GB \rightarrow CEI$	$CEI \rightarrow GB$	$GB \rightarrow CI$	$CI \rightarrow GB$	$GB \rightarrow S\&P500$	$S\&P500 \rightarrow GB$	$GB \rightarrow VIX$	$VIX \rightarrow GB$
0.05	0.9038	**0.1091**	0.28907	**0.10479**	0.28907	**0.3573**	0.28907	0.2659	0.28907	0.1451
0.1	**0.01066**	0.9105	**0.02179**	0.39221	**0.02179**	0.6066	**0.02179**	**0.0650**	**0.02179**	0.1463
0.15	**0.09457**	0.4387	**0.09624**	0.68279	**0.09624**	0.6814	**0.09024**	0.11557	**0.09624**	0.2035
0.2	**0.01091**	**0.1097**	**0.10524**	0.41056	**0.01524**	**0.0639**	**0.01524**	0.18802	**0.01524**	0.4085
0.25	**0.10557**	**0.1051**	0.55410	**0.07352**	**0.15041**	0.1849	**0.105041**	0.18262	**0.05041**	0.4564
0.3	**0.02657**	**0.096**	**0.02948**	**0.07226**	**0.02948**	**0.0631**	**0.02948**	0.3108	**0.02948**	0.3133
0.35	**0.01241**	**0.1.652**	**0.01514**	0.92611	**0.01514**	0.3045	**0.01514**	0.46082	**0.01514**	0.3704
0.4	**0.04547**	0.2094	**0.04517**	0.86951	**0.04517**	**0.1055**	**0.04517**	0.5203	**0.04517**	0.3282
0.45	**0.02723**	**0.1007**	**0.03890**	0.92072	**0.0389**	0.7488	**0.0389**	**0.06043**	**0.0389**	0.2873
0.5	**0.05896**	0.4894	**0.06020**	0.14873	**0.0602**	0.8122	**0.0602**	0.50964	**0.0602**	**0.0363**
0.55	**0.10608**	**0.0274**	**0.01121**	0.13140	**0.0112**	0.6393	**0.01127**	**0.50167**	**0.01127**	0.4266
0.6	**0.01595**	0.2444	**0.01808**	0.25560	**0.01808**	0.5687	**0.01808**	0.51633	**0.01808**	0.4108
0.65	0.71011	**0.0223**	**0.10293**	0.27190	**0.02983**	**0.0268**	**0.02983**	0.59264	**0.02983**	0.5048
0.7	0.42516	0.3226	**0.12983**	0.16762	0.04105	**0.0305**	0.44105	0.65769	0.44105	0.554
0.75	0.88479	0.4803	0.20113	0.14652	**0.02013**	0.4725	**0.02013**	**0.05521**	**0.0113**	0.3879
0.8	0.69823	0.4575	**0.01643**	**0.10031**	**0.01063**	0.4994	**0.01654**	0.58788	**0.06543**	**0.02911**
0.85	**0.01741**	0.4923	**0.01678**	0.70443	**0.10678**	0.4525	**0.10678**	0.46266	**0.01678**	0.2836
0.9	**0.03047**	0.2619	**0.00311**	0.40319	**0.00031**	0.6667	**0.10031**	0.35571	**0.00311**	**0.2075**
0.95	0.301	0.3039	0.29867	**0.02061**	0.9867	**0.1050**	0.29867	0.57329	2.9867	0.1504

Notes: The bold values show the rejection of the null hypothesis of non-Granger-causality at 10% level of significance.

Our results are consistent with Troster et al. (2018), Hashmi et al. (2020), Reboredo and Ugolini (2020) and among others, who support the causality running from changes in conventional financial asset classes to green bonds markets, via standard causality frameworks. Furthermore, we found medium and high-tail dependence between changes in green bonds and other asset prices; these outcomes tally with Reboredo and Ugolini (2020) and Troster et al. (2018) , who reported evidence of tail dependence between green bonds and a set of energy indices. Our findings also complement the papers of Maltais and Nykvist (2020), Huynh (2020a) and Pham and Huynh (2020).

4. Conclusions

The current study examines the asymmetric time-varying relationship between green bonds and other assets, including stocks, commodities, clean energy, and bitcoin, aiming to hunt for hedging characteristics of green bonds. This study further differs from prior papers in this field by employing daily data from April 2013 to December 2019 with QRA, QQA, and quantile Granger causality techniques. We find these models are valid to explore the nexus between the considered variables at different quantiles.

The empirical findings show that other assets under study strengthen green bonds in the majority of the sample period. VIX, CI, and CEI exhibit significant association with green bonds in the long term the quantiles, while BIT and S&P 500 show a strong connection in the short, medium terms but a switch blend if negative and positive fluctuations between lower and upper tails of the distribution. More importantly, there is an overall match in the pattern for QRA and QQR; the empirical results of the latter are smaller in magnitude and much more changing from negative to positive across time scales and quantiles. These indicate that other asset appreciation and depreciation do not correspond to each other; they vary over time, and therefore, impact green bonds differently. Moreover, our quantile causality test proposed by Troster (2018) further confirm these results with robust finding across time scales and quantiles. Results specify that centering on the significant Granger causality in quantile analysis, and there is evidence of bidirectional causal connectedness between green bonds and other assets in different quantiles. Additionally, our findings document evidence of lower and higher-tail causality running from green bond changes to changes in conventional asset classes.

The asymmetric dynamic interrelatedness provides instructive implications from a portfolio diversification perspective. Because of the significant association of green bonds with stock, bitcoin, and commodity markets, green bonds offer shelter to the price oscillation in the markets under examination. Therefore, investors should be cautious about combining green bonds and other markets in the portfolio set to gain diversification benefits. Furthermore, the allocation across green bonds, financial markets, and commodities may benefit investors if they take into account the decreased hedging characteristics of green bonds at various time scales and quantiles.

Our findings are also helpful for policymakers. Obviously, our study provides straightforward insights into green bonds, an innovative instrument that not only enhances the transition to a low-carbon economy but also generates the attention of policymakers and financial managers in order to reduce risk and innovative transmission across different markets. Put differently, the diversification benefit of green bonds develops policymakers' confidence to scale up the green bond market for environmental responsibility without sacrificing economic and financial development.

Furthermore, understanding the relationship between green bonds, stock, and commodity markets is of paramount importance to global investors, especially ethical investors, since this information is crucial for gaining superior risk-adjusted returns across the allocation of conventional assets to a portfolio. Even though ethical investors aim at decarbonizing their portfolios, they still make an effort to receive healthy returns from their investments. If decarbonizing portfolios do not give incentives for moving to renewable energy sources, investors may be reluctant to green their portfolios, which hamper the migration towards a low-carbon economy. Specifically, these results would be of particular interest to those market participants who wish to invest in eco-friendly companies. In general, our paper could help highlight sustainable business strategies and construct optimal portfolios.

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