



## Interconnectedness between real estate returns and sustainable investments: A cross-quantile and quantile coherency approach

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### ABSTRACT

The real estate sector is a substantial energy consumer, contributing to a large share of global greenhouse gas emissions. Despite the known links between the real estate sector and sustainable assets, studies exploring co-movements or dependence between them are still scarce. The present paper contributes to this challenging problem by capturing and analyzing the non-linear dependence over time and frequency between real estate returns and sustainable assets - green bonds, clean energy and environmental, social, and governance (ESG) stocks. We adopt a modeling approach that utilizes both the cross-quantile and the quantile coherency method. Our empirical results indicate unidirectional dependence from the real estate sector to most sustainable assets in both tails and under normal market conditions, although bidirectional dependence in the lower quantiles. Moreover, based on recursive window estimations, when the Covid-19 period is included, green bond and real estate returns are tail-dependent both during boom and bust periods. However, in non-pandemic periods, higher dependency is found during booms. Furthermore, the returns of the green bonds are less dependent on real estate returns compared to other sustainable assets. Our findings are potentially relevant for investment portfolio and public policy decision-making.

Interestingly, there are no substantial differences in the QC of the CLE with GBLD compared to the remaining real estate indices, despite the fact that green building and clean energy activities may arguably be intrinsically connected to each other. Furthermore, in general, when the returns are very high (0.95:0.95), the coherence is weak in the longer-term frequencies. In the short-term, the effect is neither strong nor considerably deviating from the results of the left tail. Therefore, the results indicate that CLE crashes rather than booms with the real estate sector at long-term frequencies.

### 1. Introduction

The real estate sector is a substantial energy consumer. According to

EIA, buildings accounted for 29% of the US end-use energy consumption in 2020.<sup>1</sup> In this context, governments and institutions around the world have been pushing for sustainability through energy performance certificates (EPC) or other rating schemes. The main purpose of these certificates is to make sustainability-related information (e.g., energy consumption, carbon emissions) more transparent, while increasing incentives for both real estate companies and households towards more energy efficient and sustainable properties (e.g., Bio Intelligence Service et al., 2013). In addition to governmental initiatives, real estate investment trusts (REITs) and other companies in the real estate sector are becoming more aware of environmental issues. According to the National Institute of Building Science (2016), equity REITs have shown interest in upgrading their energy efficiency. Furthermore, reports from

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<sup>1</sup> Frequently asked questions (FAQs) on the website of the U.S. Energy Information Administration (EIA). Retrieved from <https://www.eia.gov/tools/faqs/faq.php?id=86&t=1> (2021-09-15).

the industry indicate increased investments in clean energy solutions.<sup>2</sup> Consequently, the connections between real estate and sustainable investments are becoming larger and increasingly more relevant.

Given that large investments are necessary, financial markets and investors are crucial to reducing energy consumption in the building sector (WEF, 2016). A possibility of investors providing capital to sustainable activities is investing on green bonds (Reboredo, 2018), which is becoming a more frequent manner to finance green projects within the real estate sector.<sup>3</sup> Many institutional investors are also influenced by society to enhance the performance of environmental, social, and governance (ESG) aspects of their real estate investments (Bauer et al., 2011). Despite the growing importance of sustainability over the real estate sector and investor portfolios, it is still necessary to further investigate the relationship between real estate and sustainable assets under a portfolio perspective.<sup>4</sup> Kaminker and Stewart (2012) find that institutional investors are searching for assets with stable returns that are not highly correlated with other asset classes. Hence, given that many institutional investors have both sustainable and real estate assets in their portfolio,<sup>5</sup> the correlation or dependence between them could be important for the diversification opportunities. As emphasized in Rua and Nunes (2009), co-movement of portfolio assets is essential to know about when evaluating overall risks in portfolios and when considering potential diversification benefits.

We argue that real estate assets are connected with sustainable assets through different channels. Firstly, there has been increased investments in energy efficiency and clean energy solutions in the real estate sector, which may affect the dependence between the sectors. Secondly, listed REITs, real estate stocks and sustainable assets (e.g., clean energy and ESG stocks) belong to the overall equity market and might therefore be impacted by common market movements, shocks or uncertainty affecting the financial markets. Even if other studies have investigated the dependence between real estate assets (e.g., REITs) and the overall stock market, Uddin et al. (2019) find that renewable energy stocks have idiosyncratic risks that differ from the overall equity market.

Similarly, the dependence between real estate assets and sustainable investments may differ from the dependence between real estate and the overall stock market due to sector-specific risks. Thirdly, real estate and sustainable assets might be impacted by the same macroeconomic factors. For instance, interest rates affect property values through the discount rate, impacting the returns of real estate companies. In addition, many ESG or clean energy firms are involved in large-scale projects and dependent upon the low financing costs. Fixed-income sustainable assets, such as green bonds, are also affected by interest rate movements through the discount rate (Reboredo, 2018). All those theoretical linkages suggest a co-movement between the real estate sector and sustainable assets.

The present paper aims to analyze the quantile dependence between real estate and sustainable assets. To properly address these questions, we adopt methods capturing quantile dependence structures in both

<sup>2</sup> This was reported on the website of National Association of Real Estate Investment Trusts (Nareit), which is an industry organization representing a large share of existing REITs. See <https://www.reit.com/news/reit-magazine/july-august-2018/increasing-renewable-energy-real-estate> (2021-09-16).

<sup>3</sup> However, according to Hudgins (2024), the proportion of green bond proceeds for US REITs relative to total US REIT bond proceeds declined sharply in 2023.

<sup>4</sup> In this paper, sustainable assets refer to the returns of clean energy stocks, ESG stocks, and green bonds. With the real estate sector, we refer to the returns of publicly traded real estate investment trusts (REITs) and real estate stocks, not the value of each companies underlying assets. For more information, see the data section.

<sup>5</sup> According to IFC (2019), institutional investors hold between 8 and 10 percent of their total assets in real estate investments. US SIF (2020) states that out of total managed US-domiciled assets in 2020, 33 percent are invested using sustainable investing strategies, such as ESG-incorporation.

time and frequency. We apply the cross-quantilogram (CQ henceforth) proposed in Han et al. (2016) and the quantile coherency (QC henceforth) introduced in Baruník and Kley (2019). We first estimate the CQ-dependence between different quantiles of real estate and sustainable assets. This method enables the estimation of dependence during a wide range of different market conditions for both asset categories. Secondly, we implement a recursive window analysis to estimate potential time-varying changes in the CQ-estimations.

Our focus on quantile dependence is motivated by the numerous studies finding tail-dependence between a range of financial series. These studies have reported that the strength of dependence between financial assets generally differs during extreme market movements, such as during boom and bust periods.<sup>6</sup> Lastly, we implement the QC to estimate the quantile dependence between real estate and sustainable assets while controlling for potential asymmetries in the dependence across frequencies. Measuring dependence in the frequency domain is important as this relates to co-movements for investors with different investment horizons (Rua and Nunes, 2009), such as short and long-term investors. Considering that investments in real estate assets are conducted by various types of investors, this clearly motivates our adoption of the QC.

Our paper is related to different strands of the relevant literature, relating sustainable investments and real estate to the overall stock market and macroeconomic factors. Nonetheless, studies on the dependence between real estate and sustainable assets are still scarce. For instance, the existing literature highlights a dependence between clean energy investment alternatives and the stock market in general (Lundgren et al., 2018). Other studies focusing on real estate investment trusts (REITs) indicate a tail-dependence, or co-movement, with the stock market (e.g. Ling and Naranjo, 1999; Chang, 2018; Ding et al., 2014; Hiang Liow, 2012; Huang et al., 2016), and also that such a correlation is apparently time-varying (Heaney & Srianthakumar, 2012). Regarding green bonds, some evidence exists on their co-movement with other asset classes. Reboredo (2018) finds tail-dependence between green bonds and the corporate and treasury bond markets, although little or no dependence with the energy or general stock market. Similarly, Reboredo and Ugolini (2020) report that green bonds are influenced by spillovers from treasury bonds and the currency market. The authors also find that green bonds are weakly linked to the stock market although not affected by spillovers from the energy market.

Regarding macroeconomic factors, some studies investigate the linkages clean energy stocks (Ahmad, 2017; Henriques and Sadorsky, 2008; Huang et al., 2011; Kumar et al., 2012; Reboredo, 2015; Sadorsky, 2012; Managi and Okimoto, 2013; Uddin et al., 2019) and the oil market. Likewise, there are a few studies on volatility transmission between REITs and the oil market (Nazlioglu et al., 2016; Nazlioglu et al., 2020). Furthermore, there is also evidence on the connections between REITs and other macroeconomic factors, such as interest rates or term structure (e.g., Darrat and Glascock, 1993; Ling and Naranjo, 1997). However, none of those are directly linked to the main objective of the present paper.

Our results indicate unidirectional dependence from the real estate sector to most sustainable assets, in both tails and during normal market conditions, and bi-directional dependence during turbulent times. This suggests that the real estate sector is more influential in predicting returns of the sustainable assets than the opposite. We also observe that the influence of sustainable assets on the real estate market during periods of boom has increased over time.

Following this introduction, this paper is divided into four sections. Section 2 presents the methodology. Section 3 details the data. Section 4 contains the empirical results and discussion. Section 5 concludes.

<sup>6</sup> For instance, Chang (2018) finds greater dependence in the lower tail compared to the right tail when investigating the dependence between REITs and the stock market.

## 2. Methodology

In the present work, two related methods to estimate quantile dependence are adopted, namely the cross-quantilogram (CQ) and the quantile coherency (QC). The CQ and QC measure the dependence between quantiles of the independent and dependent variable.<sup>7</sup> Hence, by combining these methods is possible to properly capture the quantile dependence in both time- and frequency-domain. In the next subsections, the mathematical framework behind the methods adopted is detailed.

### 2.1. Cross-quantilogram (CQ)

Firstly, we apply the CQ introduced in Han et al. (2016) and follow their notation by letting  $y_{it}$  be a different stationary time series  $t = 1, 2, \dots, T$ . In the case below, we consider that  $i = 1, 2$ . The conditional distribution of the time series  $y_{it}$  given a series  $x_{it}$  may be defined as  $F_{y_{it}|x_{it}}(\cdot|x_{it})$ . From this,  $q_{i,t}(\tau_i)$  then refers to the conditional quantile function, being defined as  $q_{i,t}(\tau_i) = \inf\{v:F_{y_{it}|x_{it}}(v|x_{it}) \geq \tau_i\}$  with  $\tau_i \in (0,1)$ , while the unconditional quantile function may be described as  $q_{i,t}(\tau_i) = \inf\{v:F_{y_{it}}(v) \geq \tau_i\}$ .

Han et al. (2016) define the serial dependence between two events as  $\{y_{1,t} \leq q_{1,t}(\tau_1)\}$  and  $\{y_{2,t-k} \leq q_{2,t-k}(\tau_2)\}$ , with  $k$  being a positive integer determining the lag length, and  $\tau_1$  and  $\tau_2$  consisting of arbitrarily chosen quantiles. In our case, if  $y_{1,t}$  is a real estate index,  $y_{2,t}$  is then a sustainable asset index or vice versa. The CQ may be defined through Equation (1):

$$\rho_\tau(k) = \frac{E[\psi_{\tau_1}(y_{1,t} - q_{1,t}(\tau_1))\psi_{\tau_2}(y_{2,t-k} - q_{2,t-k}(\tau_2))]}{\sqrt{E[\psi_{\tau_1}^2(y_{1,t} - q_{1,t}(\tau_1))]} \sqrt{E[\psi_{\tau_2}^2(y_{2,t-k} - q_{2,t-k}(\tau_2))]}} \quad (1)$$

where  $\psi_\alpha = 1[u < 0] - \alpha$ . A measure of the quantile exceedance process – also known as quantile hit – is defined as  $\{1[y_{it} \leq q_{i,t}(\tau)]\}$ , with  $1[\bullet]$  consisting of the indicator function (e.g., Jiang et al., 2016). Thus, the CQ reflects a measure of the cross-correlation of quantile hits. By using the CQ approach it is possible to determine if an event affecting the return of a sustainability/real estate asset that exceeds a certain quantile may predict if the next  $k$ -period return for the real estate/sustainability asset will be greater or lower than an arbitrarily chosen quantile. If  $\rho_\tau(k)$  is not statistically different from zero, then no significant directional predictability exists. The sample CQ is expressed in Equation (2):

$$\hat{\rho}_\tau(k) = \frac{\sum_{t=k+1}^T \psi_{\tau_1}[y_{1,t} - \hat{q}_{1,t}(\tau_1)]\psi_{\tau_2}[y_{2,t-k} - \hat{q}_{2,t-k}(\tau_2)]}{\sqrt{\sum_{t=k+1}^T \psi_{\tau_1}^2[y_{1,t} - \hat{q}_{1,t}(\tau_1)]} \sqrt{\sum_{t=k+1}^T \psi_{\tau_2}^2[y_{2,t-k} - \hat{q}_{2,t-k}(\tau_2)]}} \quad (2)$$

The  $\hat{q}_{1,t}$  and  $\hat{q}_{2,t-k}$  may consist of estimates of both unconditional and conditional quantiles of their respective return series (Cho and Han, 2020). In the present study, the null hypothesis of  $\hat{\rho}_\tau(k) = 0$  is tested against  $\hat{\rho}_\tau(k) \neq 0$  using the Ljung and Box (1978) significance test for

<sup>7</sup> There are many studies discussing the benefits of using CQ instead of other common methods to measure dependence that currently exists in the finance literature. For instance, both Jiang et al. (2016) and Labidi et al. (2018) points out that the CQ is superior to quantile-regression when measuring dependence or relationships between quantiles of variables. While the CQ measures the quantile dependence using quantiles of both the dependent variable and a predictor variable, quantile-regression only enables to study the dependence using the quantiles of the dependent variable. Labidi et al. (2018) and Uddin et al. (2019) argues that the CQ is superior to copulas as the latter cannot include lags and provides less informative dependence structures. Interested readers are referred to these papers for more details.

autocorrelation. The test statistic is defined following Equation (3):

$$\hat{Q}_\tau(p) = T(T+2) \sum_{k=1}^p \frac{\hat{\rho}^2(k)}{T-k} \quad (3)$$

The results of the CQs are presented through both heatmaps and recursive window analysis, similar to other studies applying the CQ to study quantile dependence between financial assets (e.g., Uddin et al., 2019). The  $x$ - and  $y$ -axes of the heatmaps are either the return series of a real estate index on the  $y$ -axis and an index of a sustainable asset on the  $x$ -axis, or vice versa. The quantiles on the respective axes consist of 11 quantiles ranging from 0.05 to 0.95. Regarding the CQ heatmaps, we report the results of estimations considering one-to five-day lags. By also estimating a recursive window, we investigate if the CQ dependence between real estate and sustainable assets changes over time. We adopt an initial window of 250 days that progresses on a daily basis. Confidence intervals are derived from a bootstrap procedure (Han et al., 2016).

### 2.2. Quantile coherency (QC)

Following Baruník and Kley (2019), we let a stationary process be defined as  $(\mathbf{X}_t)_{t \in \mathbb{Z}}$  with the components ranging from  $X_{t,j_1}$  to  $X_{t,j_n}$ . In the present work, these refer to the real estate and sustainability series. The matrix of quantile cross-covariance kernels may be defined following Equation (4) and Equation (5):

$$\Gamma_k(\tau_1, \tau_2) := \left( \gamma_k^{j_1 j_2}(\tau_1, \tau_2) \right)_{j_1, j_2=1 \dots n} \quad (4)$$

$$\gamma_k^{j_1 j_2}(\tau_1, \tau_2) = \text{Cov}\left(\mathbf{I}\{X_{t+k, j_1} \leq q_{j_1}(\tau_1)\}, \mathbf{I}\{X_{t, j_2} \leq q_{j_2}(\tau_1)\}\right) \quad (5)$$

Where  $\mathbf{I}(\bullet)$  is an indicator function,  $\tau_1, \tau_2 \in [0, 1]$  and  $j_1$  and  $j_2$  are elements of the set  $\{1 \dots n\}$ . The terms  $q_{j_1}$  and  $q_{j_2}$  consist of the quantile functions of the marginal distributions ( $F_1$  and  $F_2$ ) of two stationary processes  $X_{t, j_1}$  and  $X_{t, j_2}$ , with the quantile functions defined as  $q_j(\tau) = F_j^{-1}(\tau)$ . Baruník and Kley (2019) then define the dynamic dependence, or quantile-coherency kernel for  $X_{t, j_1}$  and  $X_{t, j_2}$ , as detailed in Equation (6):

$$\mathfrak{H}^{j_1 j_2}(\omega; \tau_1, \tau_2) = \frac{\check{f}^{j_1 j_2}(\omega; \tau_1, \tau_2)}{\left(\check{f}^{j_1 j_1}(\omega; \tau_1, \tau_2)\check{f}^{j_2 j_2}(\omega; \tau_1, \tau_2)\right)^{1/2}} \quad (6)$$

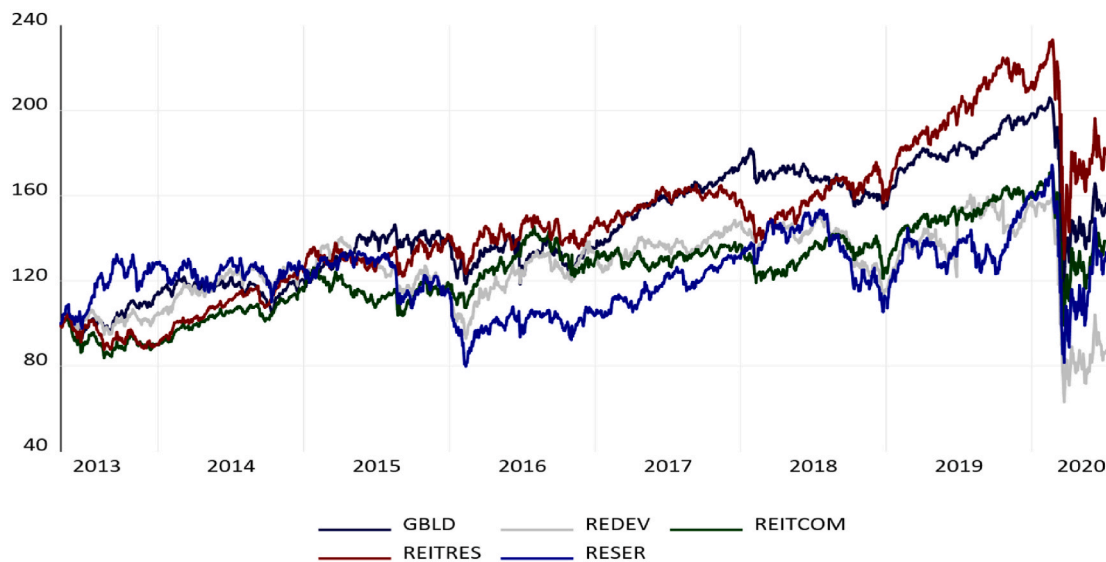
Where  $\check{f}(\omega; \tau_1, \tau_2)$  is the matrix of cross-spectral kernels in the frequency domain, and  $\check{f}^{j_1 j_2}(\omega; \tau_1, \tau_2)$  being calculated following Equation (7):

$$\check{f}^{j_1 j_2}(\omega; \tau_1, \tau_2) := (2\pi)^{-1} \sum_{k=-\infty}^{\infty} \gamma_k^{j_1 j_2}(\tau_1, \tau_2) e^{-ik\omega} \quad (7)$$

With  $\omega \in \mathbb{R}$  and  $\tau_1, \tau_2 \in [0, 1]$ . As  $\check{f}^{j_1 j_2}(\omega; \tau_1, \tau_2)$  is complex valued, it may be decomposed into a real and imaginary part. In the present study, we focus only on the real part. As mentioned in Baruník and Kley (2019), the QC is similar to the CQ as both focus on serial dependence between two events. However, the former is defined in the frequency domain instead of the time domain. Therefore, using both the QC and the CQ method, enables to perform a deeper analysis of the quantile dependence between the real estate market and sustainable assets, since such a methodological combination captures both frequency and time domains.<sup>8</sup> Before performing the CQ analysis, the returns of each asset are adjusted for heteroscedasticity through univariate GARCH models. This

<sup>8</sup> The QC is applied to several studies within the financial literature and in the field of energy economics. For example, refer to a study applying the QC to analyze the dependence between crude oil and exchange rates (Tiwari et al., 2019), and one focusing on networks of stocks (Baumöhl and Shahzad, 2019).

(a) Data in levels



(b) Returns

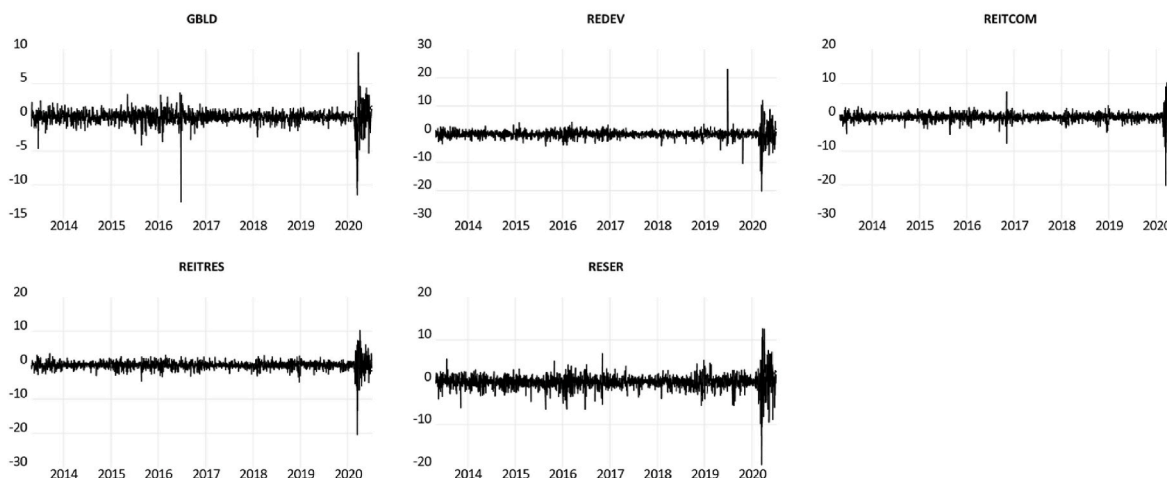


Fig. 1. Plots of the real estate data

Notes: In (a), the vertical axis represents the index value, which is set to 100 in the first time point of the series (i.e., April 30, 2013). In (b), the vertical axis shows log returns (in percent).

procedure follows the approach adopted by Barunik and Kley (2019).

### 3. Data

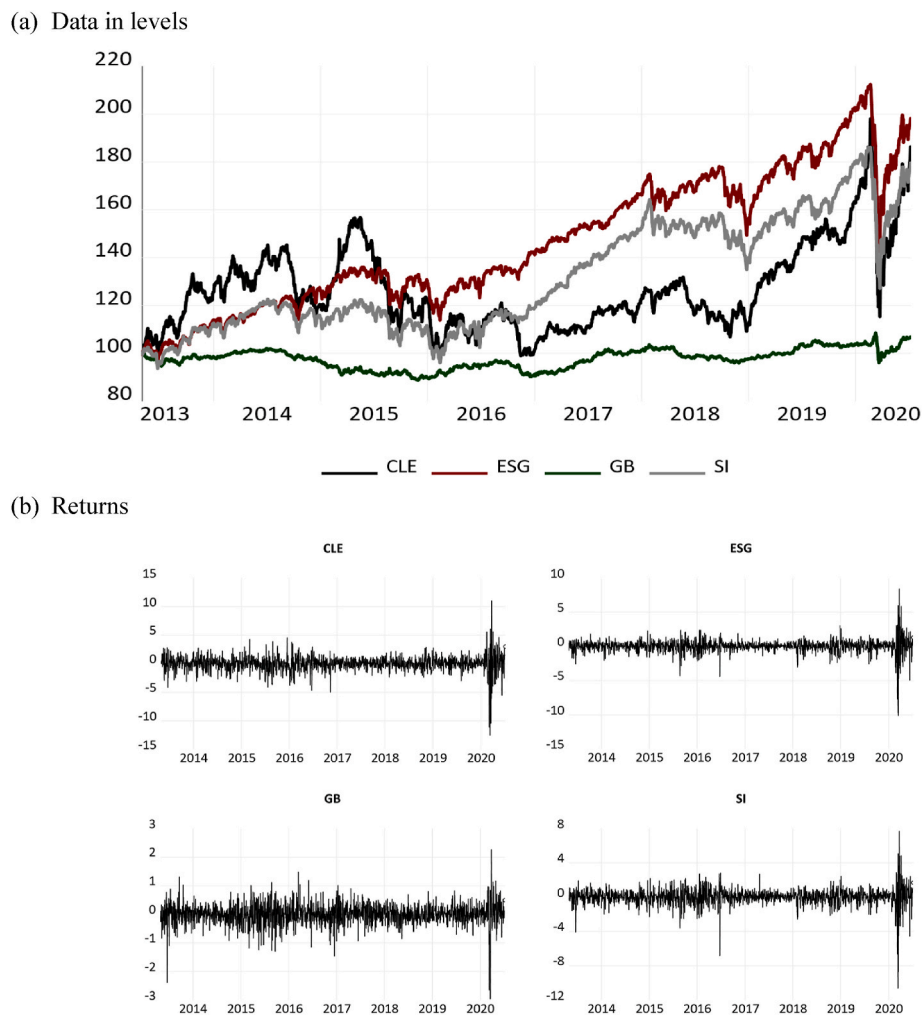
To explore the dependence between the real estate sector and sustainable assets, we use five real estate indices, each capturing different parts of the market. In the category of real estate investment trusts (REITs), our indices include the United States Residential REIT Index (REITRES) and the United States Commercial REIT Index (REITCOM). To capture the remaining part of the US real estate market, our sample also includes the United States Real Estate Service Index (RESER) and United States Real Estate Development and Operations Index (REDEV).<sup>9</sup> Moreover, we include the MSCI Global Green Building Index (GBLD),

which consists of companies deriving their income from green building, with many operating as REITs.

In the category of sustainable assets, the following four indices are included in our sample: S&P Green Bond Select Index (GB), S&P Clean Energy Index (CLE), MSCI World ESG Leaders (ESG), and the Dow Jones Sustainability Index World (SI). Hence, our sample of sustainable assets includes securities from different types of sectors as well as distinct financial instruments. All data are downloaded from Datastream as total return indices denoted in USD, spanning a daily frequency from April 30, 2013, to July 6, 2020<sup>10</sup>. The data is transformed into logarithmic returns to perform the estimations. The selected time period is based on the data availability for all indices. After cleaning the data (e.g., holidays), the dataset includes 1806 observations.

<sup>9</sup> Tickers are in parentheses: United States Residential REIT index (TRXFLDUSPREIR), United States Commercial REIT index (TRXFLDUSPREIC), United States Real Estate Service index (TRXFLDUSPREAS), and United States Real Estate development and operations index (TRXFLDUSPREAL).

<sup>10</sup> However, we use the MSCI World ESG Leaders index in local currency.



**Fig. 2.** Plots of the sustainable assets  
 Notes: In (a), the vertical axis represents the index value, which is set to 100 in the first time point of the series (i.e., April 30, 2013). In (b), the vertical axis shows log returns (in percent).

#### 4. Empirical results

We present our empirical results in four subsections. The first subsection shows an exploratory data analysis. In the second subsection, we present the results of the cross-quantilogram (CQ) estimations. In the third subsection, we explore the time-evolution of the dependence structures by presenting the CQ correlation for the tails of the return distributions estimated with recursive rolling windows. In the fourth

subsection, we present the results of the QC analysis, showing the dependence in the joint distribution of returns of real estate and sustainable assets across different frequencies.

##### 4.1. Exploratory data analysis

The time trends (a) and returns (b) of our included real estate and sustainable assets are depicted in Figs. 1 and 2, respectively. In general,

**Table 1**  
 Descriptive statistics.

Variable	Mean (%)	Median (%)	MAD	SD (%)	Skewness	Kurtosis	Normality	ADF	PP
GBLD	0.020	0.055	0.438	1.066	-2.295	35.28414	80,016.05***	-14.132(9)***	-33.753***
REDEV	-0.007	0.042	0.637	1.693	-0.308	45.25374	13,4378.3***	-12.151(8)***	-42.127***
REITCOM	0.018	0.078	0.571	1.367	-2.133	38.57231	96,590.25***	-12.701(10)***	-47.727***
REITRES	0.032	0.112	0.571	1.361	-2.313	42.30933	11,7888.2***	-13.797(9)***	-45.929***
RESER	0.016	0.052	0.804	1.800	-0.908	18.56032	18,467.93***	-15.156(6)***	-41.216***
CLE	0.030	0.099	0.601	1.303	-1.167	19.0196	19,721.06***	-13.200(8)***	-39.266***
ESG	0.036	0.079	0.353	0.916	-1.456	28.5815	49,882.76***	-13.144(9)***	-45.109***
GB	0.003	0.011	0.194	0.359	-0.689	10.01255	38,43.224***	-17.639(6)***	-39.970***
SI	0.029	0.067	0.403	0.930	-1.517	24.20631	34,533.66***	-13.805(9)***	-42.529***

Notes: In the above table, median absolute deviation is denoted by MAD, SD refers to standard deviation, Normality represents the test statistic of the Jarque-Bera test, ADF is the Augmented Dickey-Fuller test for a unit root with a constant and trend included (optimal lag length in parentheses), and PP is the Phillips-Perron unit root test. The null hypothesis of the unit root tests is that the variable has a unit root, while the null hypothesis of the Jarque-Bera test is that the variable is normally distributed. Significance at the 1% level is denoted by \*\*\*.

**Table 2**  
Pearson correlation matrix.

	CLE	ESG	GB	GBLD	REDEV	REITCOM	REITRES	RESER	SI
CLE	1.00								
ESG	0.76	1.00							
GB	0.12	-0.03	1.00						
GBLD	0.66	0.72	0.28	1.00					
REDEV	0.57	0.70	0.08	0.63	1.00				
REITCOM	0.55	0.72	0.13	0.63	0.74	1.00			
REITRES	0.48	0.63	0.14	0.57	0.67	0.88	1.00		
RESER	0.61	0.78	0.02	0.61	0.75	0.70	0.60	1.00	
SI	0.77	0.93	0.18	0.77	0.63	0.63	0.55	0.70	1.00

it is worth noting that the Covid-19 pandemic severely impacts both real estate and sustainable asset level series, with the largest drop for the REDEV index. During our sample period, REITRES and GBLD show a superior performance compared to the remaining real estate indices.

As shown in Fig. 2, the graph suggests that the SI and ESG indices, like most real estate series in Fig. 1, experienced increases over the sample period, up until the Covid-19 period. From Fig. 2 (a), we observe decreasing index levels of GB and CLE during the years in the middle of our sample. Based on the substitution arguments between oil and clean energy firms put forward in Managi and Okimoto (2013) and Uddin et al. (2019), one explanation for the low CLE performance may be the low oil price during this period.

The descriptive statistics and unit root tests of the returns are reported in Table 1. There are positive mean logarithmic returns for all variables except REDEV. In most cases, the real estate variables have a higher standard deviation and median absolute deviation (MAD) compared to the sustainable assets. This might reflect that there are fewer assets in their index composition, resulting in more fluctuations.

All return series have negative skewness, indicating that their distributions are skewed to the left. The rejection of the null hypothesis in the Jarque-Bera (Bera and Jarque, 1981) tests indicates that our variables are not normally distributed, which is consistent with the respective stylized fact found in the literature. The high values of kurtosis - much larger than three - indicate that large losses and gains are more likely compared with what would be assumed under a Gaussian distribution.

In addition, the results of the augmented Dickey-Fuller or ADF test (Dickey and Fuller, 1979) and the Phillips-Perron unit root test (Phillips and Perron, 1988) suggest that the variables are stationary.<sup>11</sup> The linear correlations between all return series are reported in Table 2. In line with our previous observations, the correlations between ESG, SI, and the real estate variables are higher compared to the correlations between the real estate and GB and CLE. In some cases, such as between ESG and RESER, the correlation is very high.

The GB series shows low correlation with most of the remaining variables - some of them close to zero - with its greatest correlation with GBLD (i.e., 0.28). Thus, this suggests that companies involved in green building may be more dependent on returns of GB compared to the rest of the real estate sector.

#### 4.2. Cross-quantilogram (CQ) results

The results of the CQ analysis are depicted in Figs. 3–6, and are presented in heatmaps with the quantiles of respective variable reflected in the axes. In the heatmaps, red color indicates positive CQ-correlation while blue color is negative correlation. Strong positive correlations have a stronger red color, while a lighter red indicates a weaker positive correlation. A strong blue color represents a strong negative correlation,

<sup>11</sup> We present the results from the ADF test using a maximum lag length of ten. It is worth mentioning that, in our case, changing the maximum lag does not impact any of the reported results.

while a lighter blue indicates a weaker negative correlation. The green color is displayed if the correlations (for that specific quantile combination) is insignificant based on the 5 % significance level.<sup>12</sup> The arrow shows the direction of the correlation. The left side of the figures shows the direction from the real estate returns to the sustainability returns while the right part displays the correlation in the direction from the sustainability to real estate. The axes consist of 11 quantiles ranging from periods of extremely low returns (quantile 0.05) to periods of extremely high returns (quantile 0.95).

If we start by looking at the CQ between the Green Bonds (GB) and the real estate returns in Fig. 3, red color in the lower left corner indicates they are dependent in periods of extreme low returns (e.g., quantile 0.05). This is most apparent on the left side of the figure - i.e., when the direction of dependence goes from the real estate sector to sustainable assets and for the first lag. This may be interpreted as returns of green bonds assets being more likely to be low on the next trading day after low returns observed in the real estate sector. There is also significant dependence on the top right corner for many of the heatmaps, suggesting a connection between these sectors during boom periods. However, such a correlation is weaker in the lower left corner and not as widespread. When looking at the reverse direction (right-hand side of the figures), we do not see any significant pattern of dependence. Hence, extremely positive or negative returns of GB are not followed by an increased likelihood of extremely low or high returns in the real estate assets the next day. Given the tail-dependence in the lower left corner, this implies that green bonds do not add any diversification benefits to a real estate portfolio during turbulent times.

#### GBLD → GB.

When looking at the CQ between the real estate indices and the rest of the sustainable assets in Figs. 4–6, one may notice a positive dependence concentrated in the lower left corner for almost all heatmaps in both directions (i.e., on both the left and right side of the figures). Hence, the connection between real estate and sustainable assets is bi-directional during turbulent times, meaning that both sectors are influencing and impacting each other. This is in accordance with the findings for REITs, where tail-dependence has been found with the stock market (e.g. Chang, 2018; Huang et al., 2016; Rong and Trück, 2014). This is also common for financial markets in general, where extreme turbulence impacts all assets and sectors.

When looking at quantile combinations, except for the lower left corner, the directionality generally goes from the real estate to sustainable assets but not the other way around. Regarding the results of CLE (Fig. 5) and SI (Fig. 6) in the same direction, we observe significant results in most of the quantiles. This indicates that the real estate sector is leading sustainable asset movements in most quantile combinations. One potential explanation might be that increased awareness of clean energy solutions in the real estate sector makes ESG and sustainable assets more affected by the performance of the real estate sector. The

<sup>12</sup> In a technical manner, this is done by setting the cross-quantilogram correlations to 0 for those cells in the heatmaps where the correlations are insignificant.



**Fig. 3.** CQ estimations between the GB and real estate indices

Notes: The vertical axis is the quantiles of the variable on the left-hand side of the arrow while the horizontal axis is the quantiles of the right-hand side variable. The arrow shows the direction of the correlation. The green color is displayed for quantile-combinations where the Box-Ljung test statistic is not significant based on the 5% significance level, while the red and blue colors display significant positive and negative correlations, respectively.

tail-dependence in the upper and lower corners implies low diversification benefits for investors during extreme market movements.

In contrast to other real estate variables, GBLD shows a bi-directional connection with the CLE, SI, and ESG, suggesting a closer dependence compared with the rest of the real estate variables. Considering that the

GBLD comprises companies that promote sustainability, environmental, and governance practices, such a result is not surprising. Hence, the returns of companies in this index are probably more likely to be impacted by the performance of the clean energy or other sustainable companies compared to the rest of the real estate sector.

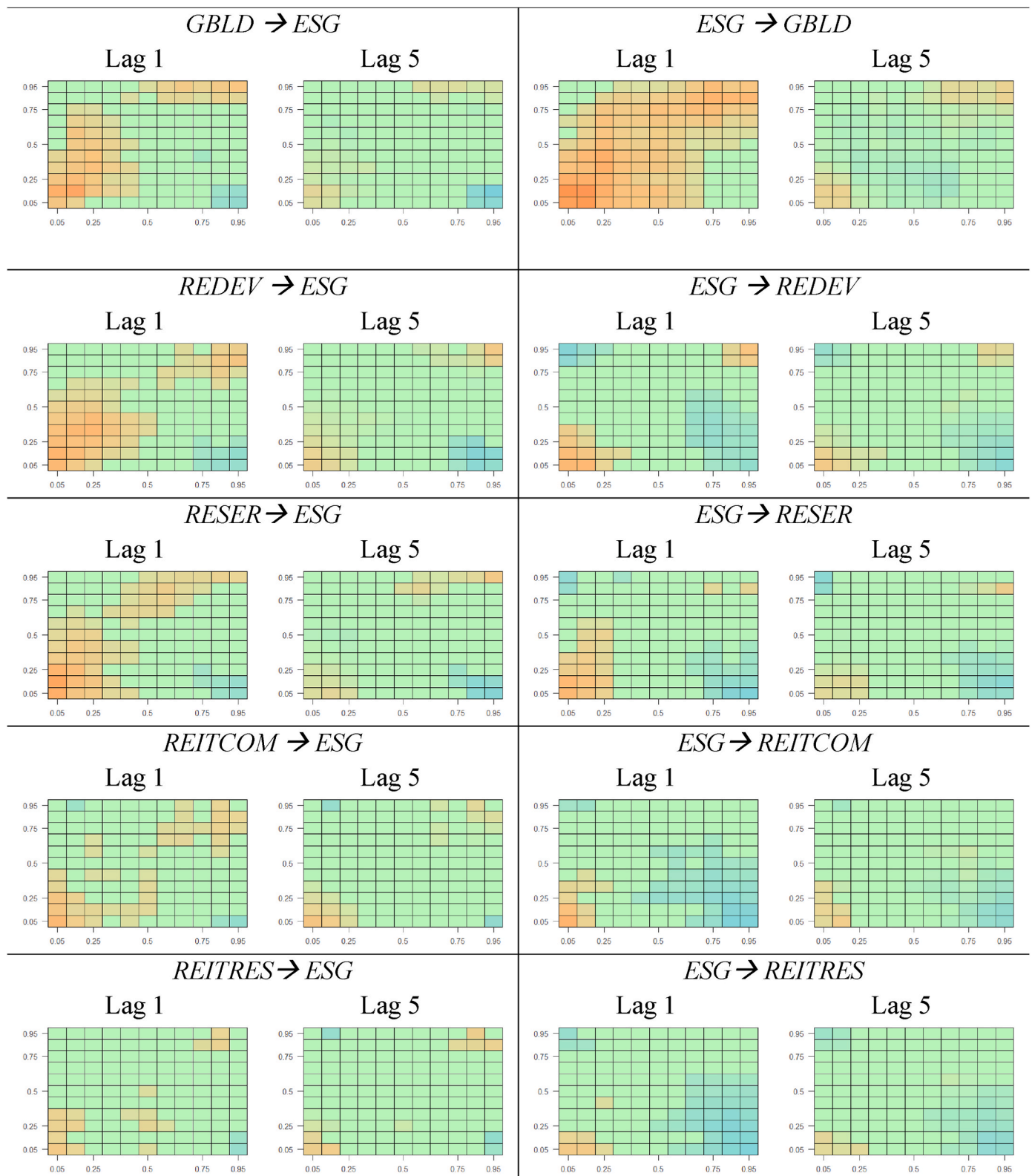


Fig. 4. CQ estimations between the ESG and real estate indices

Notes: The vertical axis is the quantiles of the variable on the left-hand side of the arrow while the horizontal axis is the quantiles of the right-hand side variable. The arrow shows the direction of the correlation. The green color is displayed for quantile-combinations where the Box-Ljung test statistic is not significant (based on the 5% significance level), while the red and blue colors display significant positive and negative correlations, respectively.

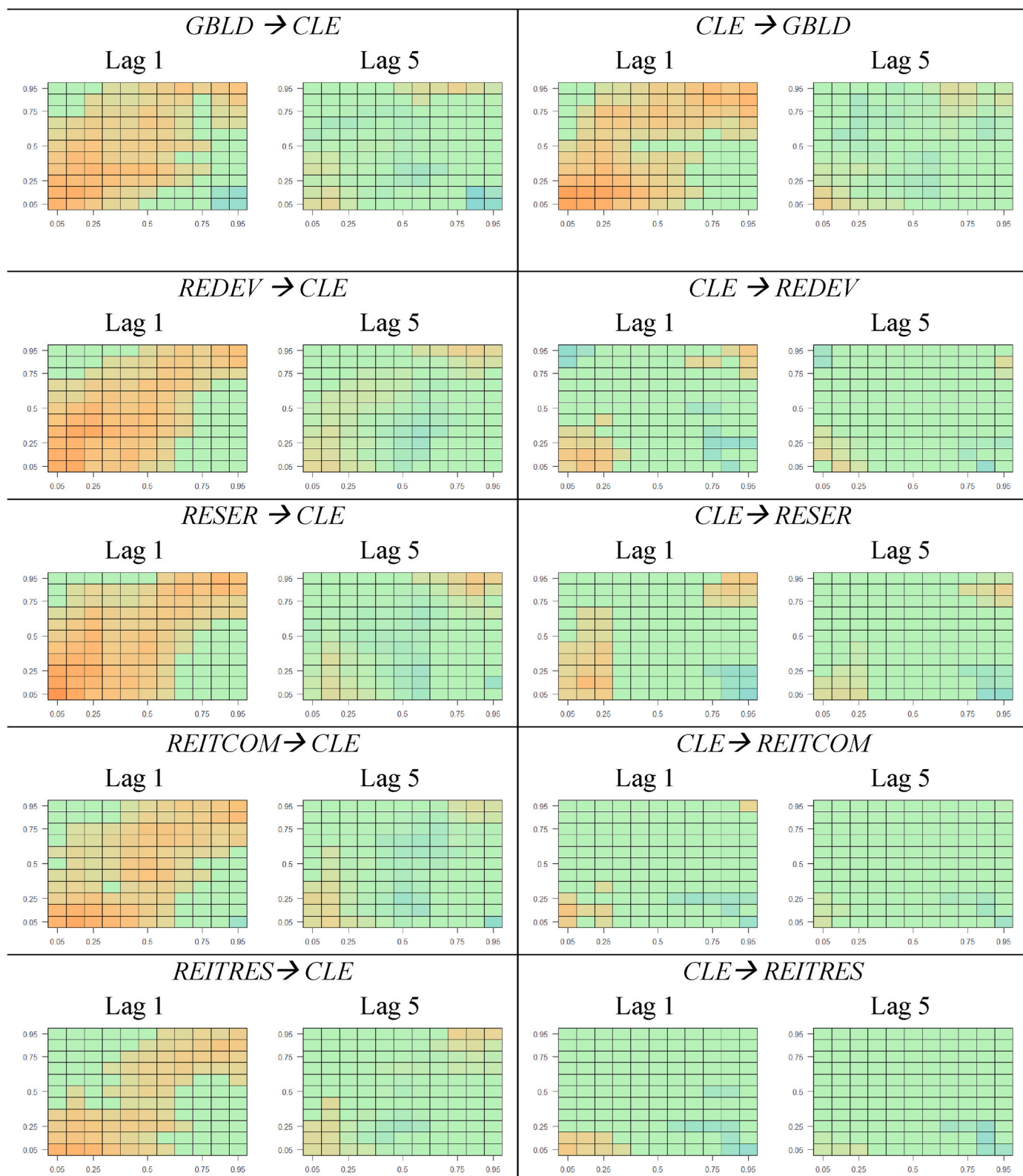
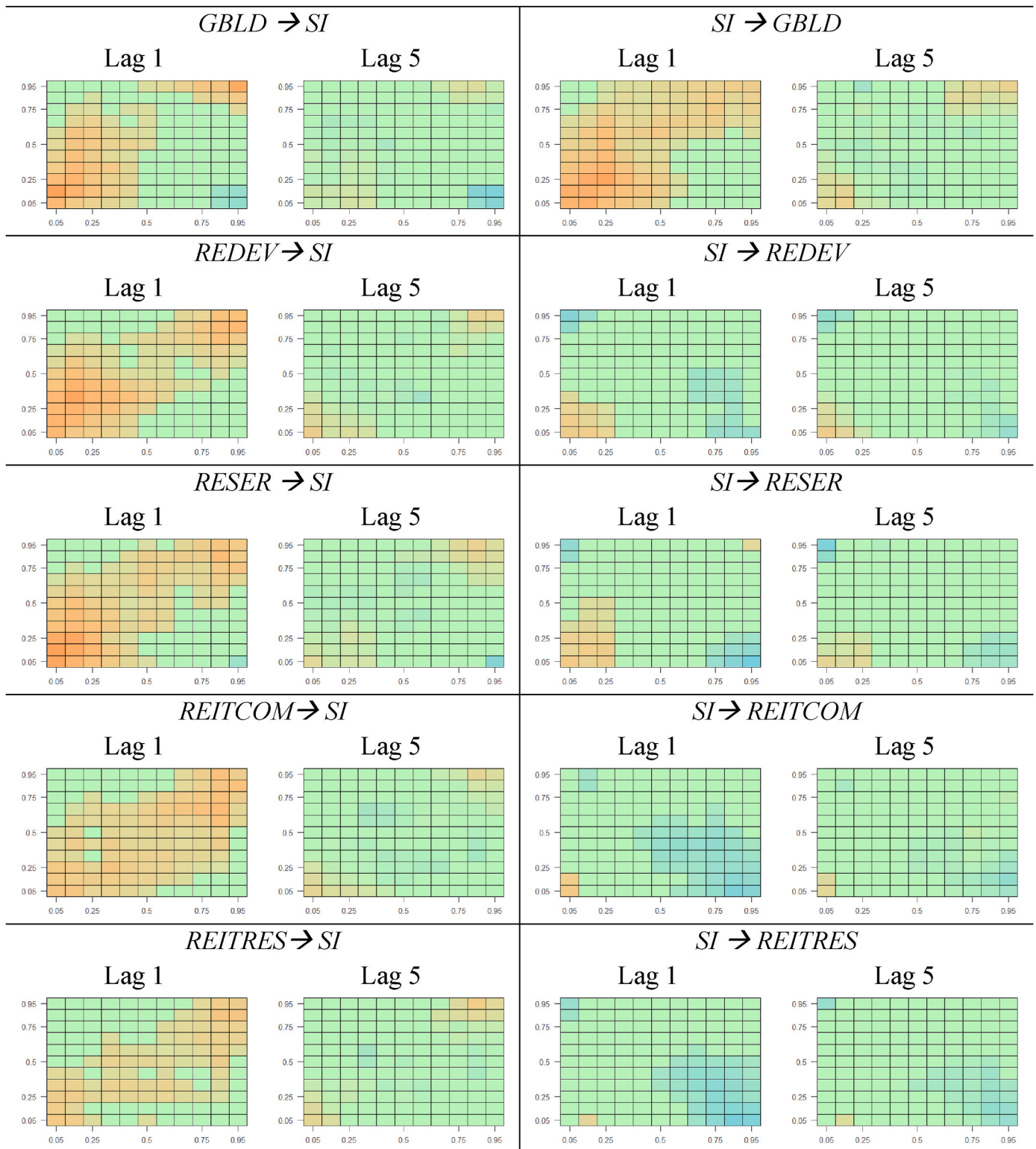


Fig. 5. CQ estimations between the CLE and real estate indices

Notes: The vertical axis is the quantiles of the variable on the left-hand side of the arrow while the horizontal axis is the quantiles of the right-hand side variable. The arrow shows the direction of the correlation. The green color is displayed for quantile-combinations where the Box-Ljung test statistic is not significant (based on the 5% significance level), while the red and blue colors display significant positive and negative correlations, respectively.



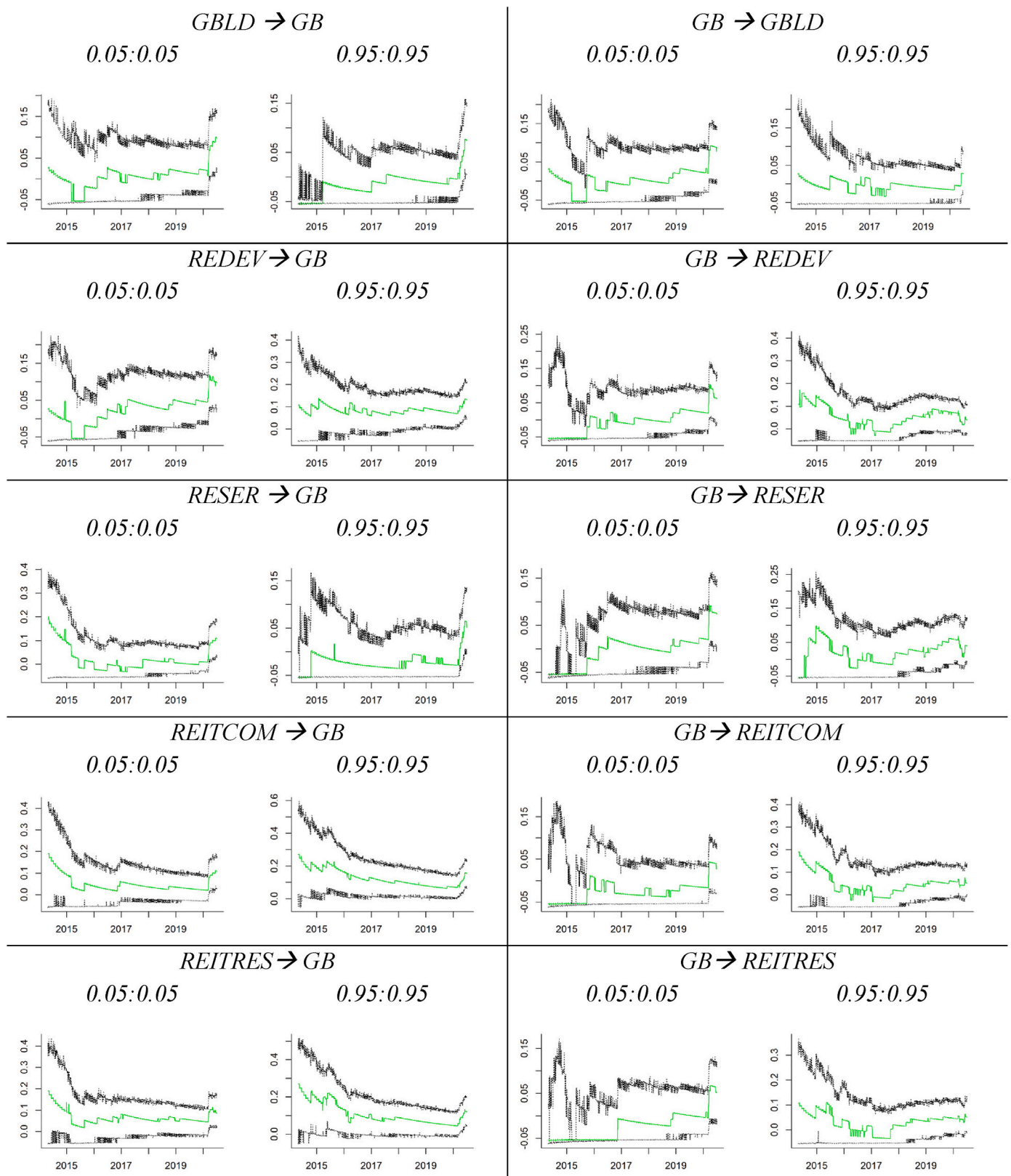
**Fig. 6.** CQ estimations between the SI and real estate indices

Notes: The vertical axis is the quantiles of the variable on the left-hand side of the arrow while the horizontal axis is the quantiles of the right-hand side variable. The arrow shows the direction of the correlation. The green color is displayed for quantile-combinations where the Box-Ljung test statistic is not significant (based on the 5% significance level), while the red and blue colors display significant positive and negative correlations, respectively.

### 4.3. Recursive rolling window estimations

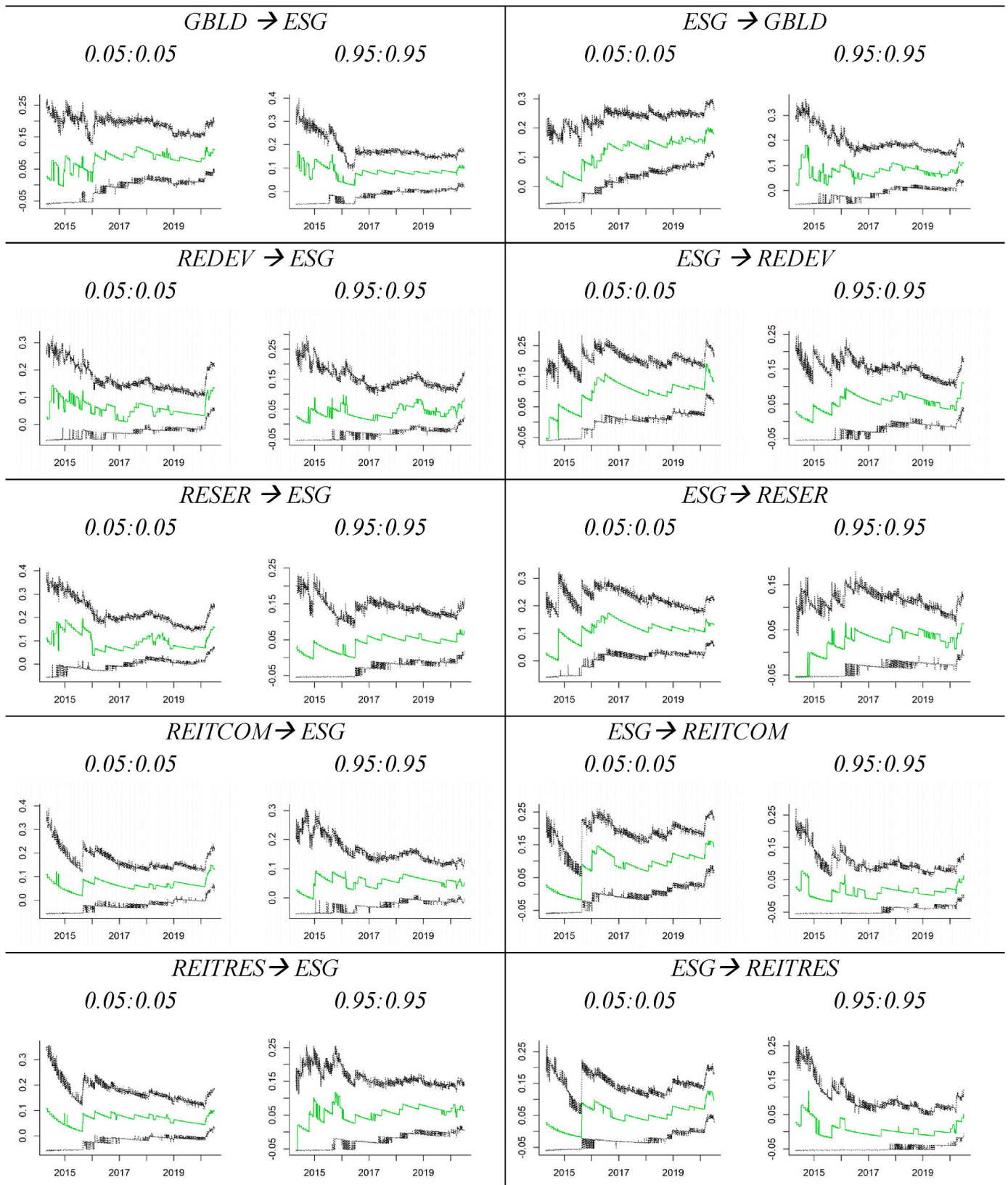
In Figs. 7–10, we present the rolling window estimations when both real estate and sustainable assets are in their respective lower (0.05:0.05) and upper tails (0.95:0.95). Recursive rolling window works

by estimating the CQ correlation for the initial window - which is set to 250 days - that advances daily and is then estimated again for the new window. This method allows us to observe the time-varying nature of the CQ correlation throughout the sample period. The correlation is captured by the green lines, while the black lines refer to the 95%



**Fig. 7.** Recursive rolling-window CQ estimations between GB and real estate indices

Notes: This figure shows the CQ-correlation for the recursive subsamples when both return series are in the left (0.05:0.05) and right tail (0.95:0.95) quantiles. The arrow reflects the direction of the correlation. The initial window length is 250 days, which then advances with 1 day at a time. The green lines are the correlation while the black lines represent the 95% confidence intervals calculated by a bootstrap method.



**Fig. 8.** Recursive rolling-window CQ estimations between ESG and real estate indices  
 Notes: This figure shows the CQ-correlation for the recursive subsamples when both return series are in the left (0.05:0.05) and right tail (0.95:0.95) quantiles. The arrow reflects the direction of the correlation. The initial window length is 250 days, which then advances with 1 day at a time. The green lines are the correlation while the black lines represent the 95% confidence intervals calculated by a bootstrap method.

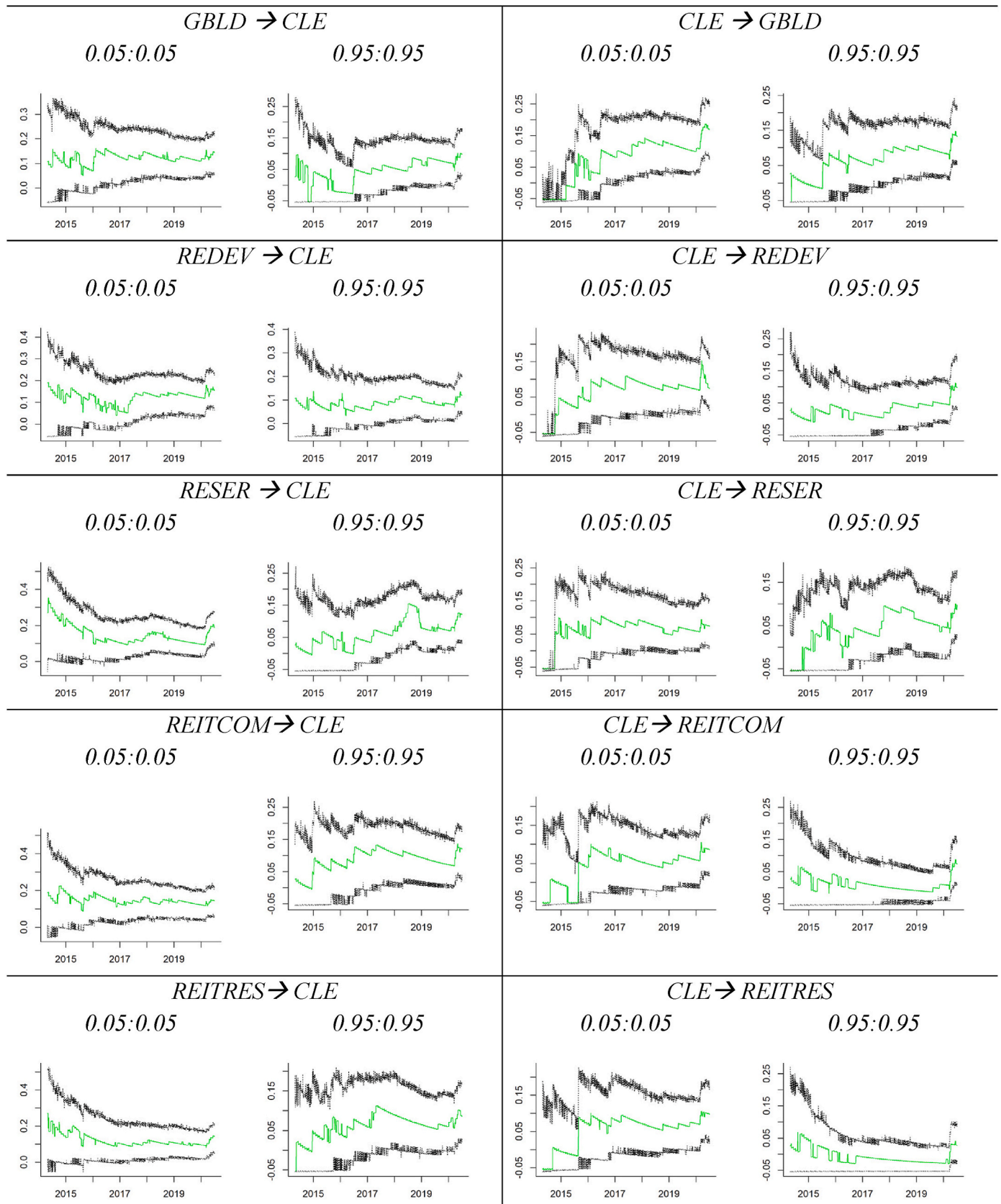
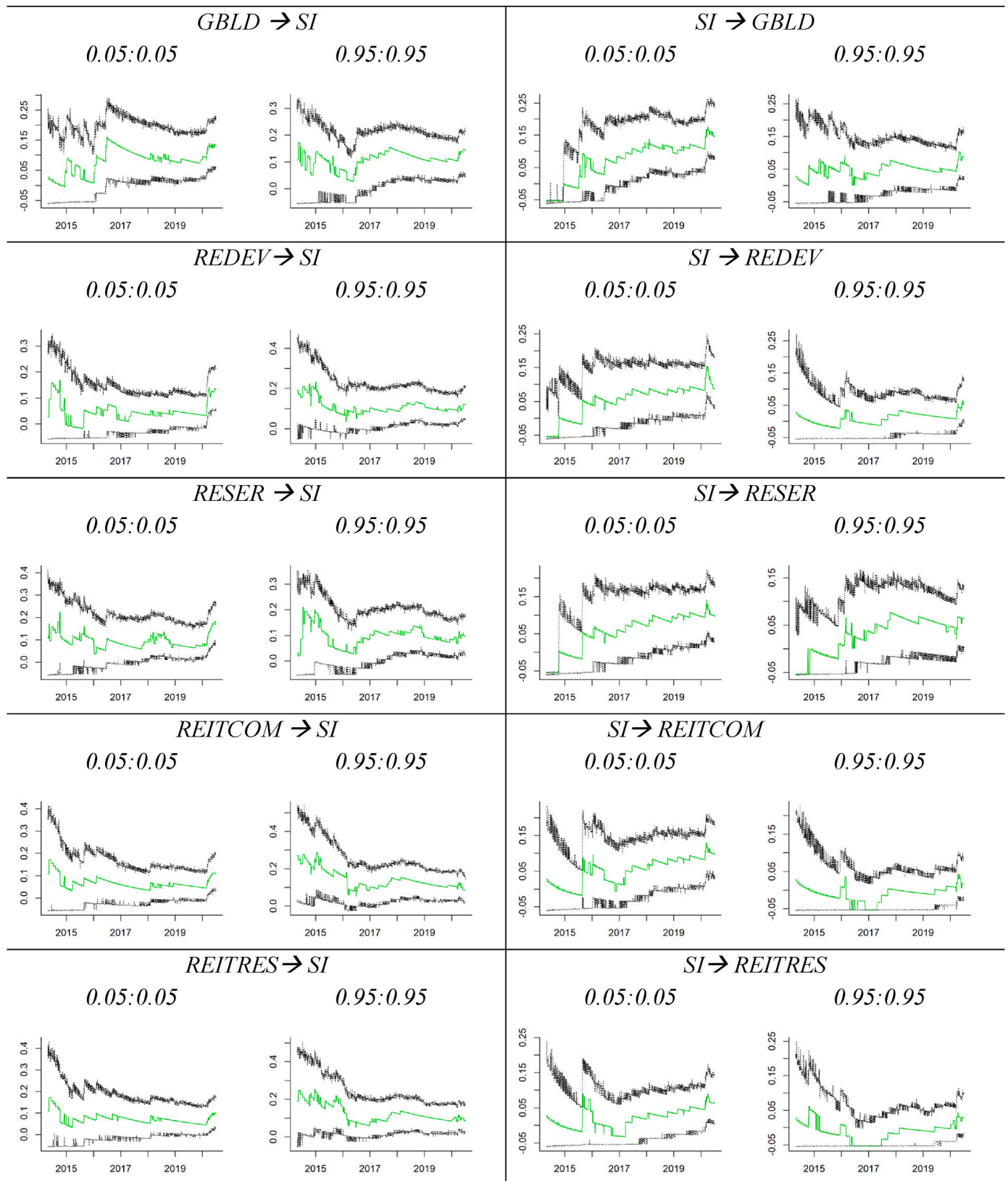
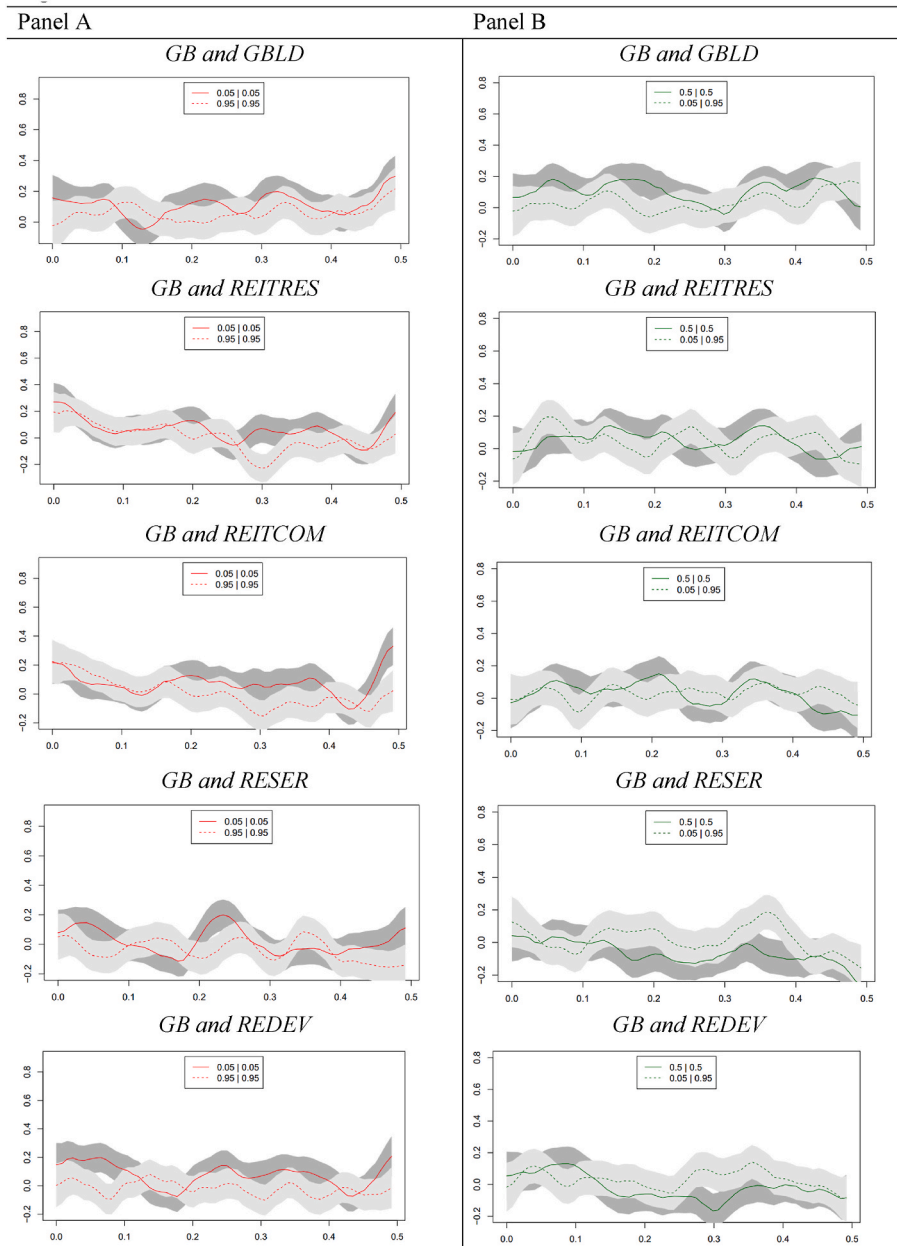


Fig. 9. Recursive rolling-window CQ estimations between CLE and real estate indices

Notes: This figure shows the CQ-correlation for the recursive subsamples when both return series are in the left (0.05:0.05) and right tail (0.95:0.95) quantiles. The arrow reflects the direction of the correlation. The initial window length is 250 days, which then advances with 1 day at a time. The green lines are the correlation while the black lines represent the 95% confidence intervals calculated by a bootstrap method.



**Fig. 10.** Recursive rolling-window CQ estimations between SI and real estate indices  
 Notes: This figure shows the CQ-correlation for the recursive subsamples when both return series are in the left (0.05:0.05) and right tail (0.95:0.95) quantiles. The arrow reflects the direction of the correlation. The initial window length is 250 days, which then advances with 1 day at a time. The green lines are the correlation while the black lines represent the 95% confidence intervals calculated by a bootstrap method.



**Fig. 11.** QC between GB and real estate returns

Notes: the vertical axis represents the strength of the coherence and the horizontal axis refers to the frequency. Panel A (left-hand side) shows the coherence of the tails while Panel B (right-hand side) shows the coherence in the median and when the return series are in opposite tails. In both panels, the light grey color represents the 95% level confidence band for the dotted lines while the confidence band in dark grey relates to the filled lines.

confidence intervals.

In general, the most notable event occurs at the end of the sample period, during the outbreak of the Covid-19 pandemic, in the year 2020. The correlations increase substantially when the returns are both in their lower (0.05:0.05) and higher quantiles (0.95:0.95) for almost all return combinations. The increased correlation levels in the lower quantiles may be explained by financial market crashes observed in early 2020, affecting most markets.

One interesting finding of the recursive rolling window estimations may be found in the results from the real estate sector to the GB shown in Fig. 7, when both return series are in their lower quantiles (0.05:0.05). Before the Covid-19 crisis, for most combinations the lower confidence band was below zero and should not have indicated any significant tail-dependence in the CQ. However, when the recursive window also spans the time of the turbulence involving the Covid-19 pandemic, the

confidence interval is greater than zero, indicating unidirectional dependence from the real estate sector to GB.

Because all returns decrease simultaneously, the correlations are positive. The increased correlations in the higher quantiles (0.95:0.95) might be explained by the reversal of the markets a couple of weeks after the beginning of the Covid-19 crisis.

Hence, this could explain the significant tail-dependence found for GB and the real estate sector in the CQ heatmap (Fig. 3), considering that this estimation is based on the full sample window. The tail-dependence between real estate and GB in the left tail is mostly connected to the crisis caused by the Covid-19 pandemic. If we instead analyze the dependence between GB and real estate when they are in their right tails (0.95:0.95), we then observe that the confidence interval is above zero during parts of the periods, even before the beginning of the Covid-19 crisis for some of the variables (REDEV, REITCOM, and REITRES).

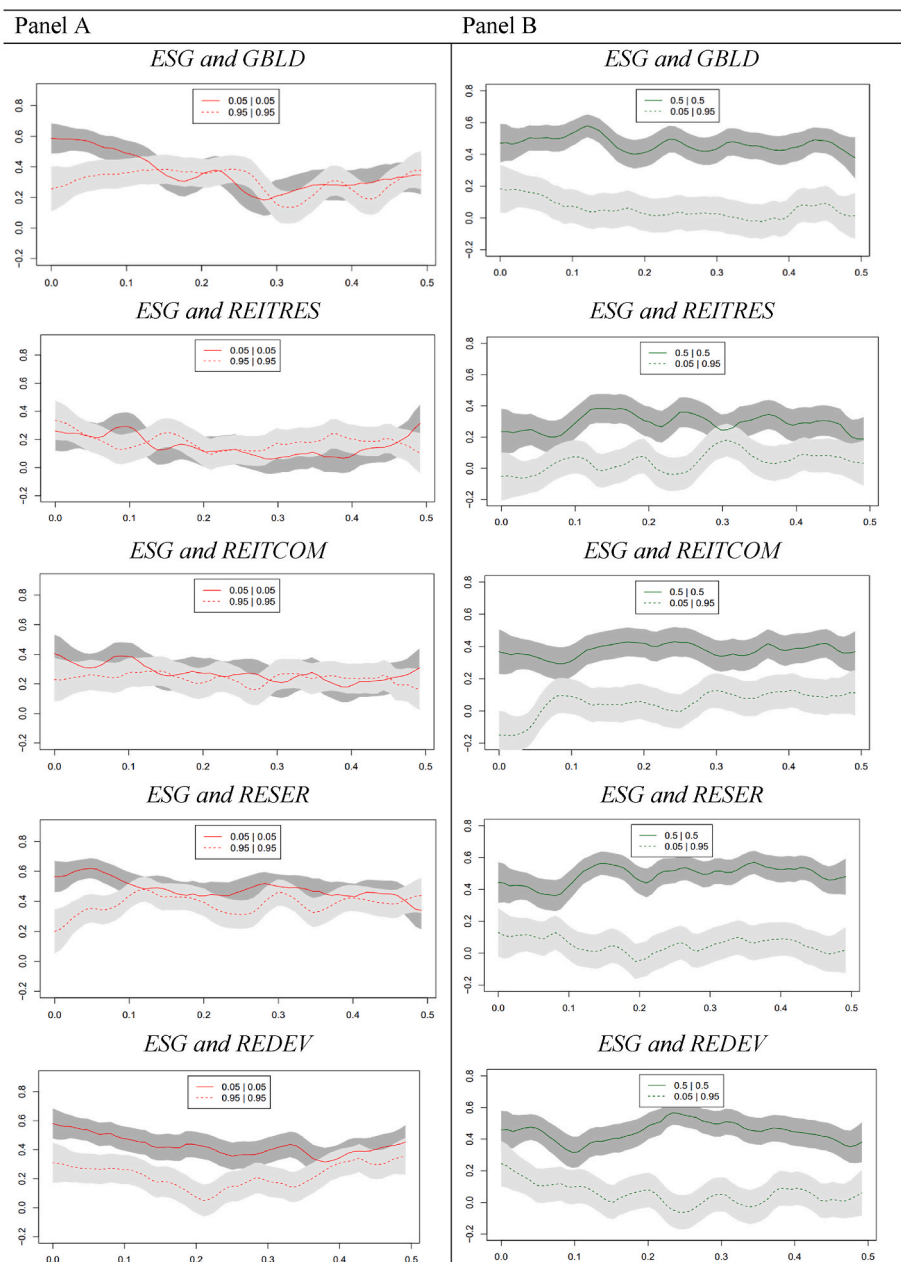


Fig. 12. QC between ESG and real estate returns

Notes: the vertical axis represents the strength of the coherence and the horizontal axis refers to the frequency. Panel A (left-hand side) shows the coherence of the tails while Panel B (right-hand side) shows the coherence in the median and when the return series are in opposite tails. In both panels, the light grey color represents the 95% level confidence band for the dotted lines while the confidence band in dark grey relates to the filled lines.

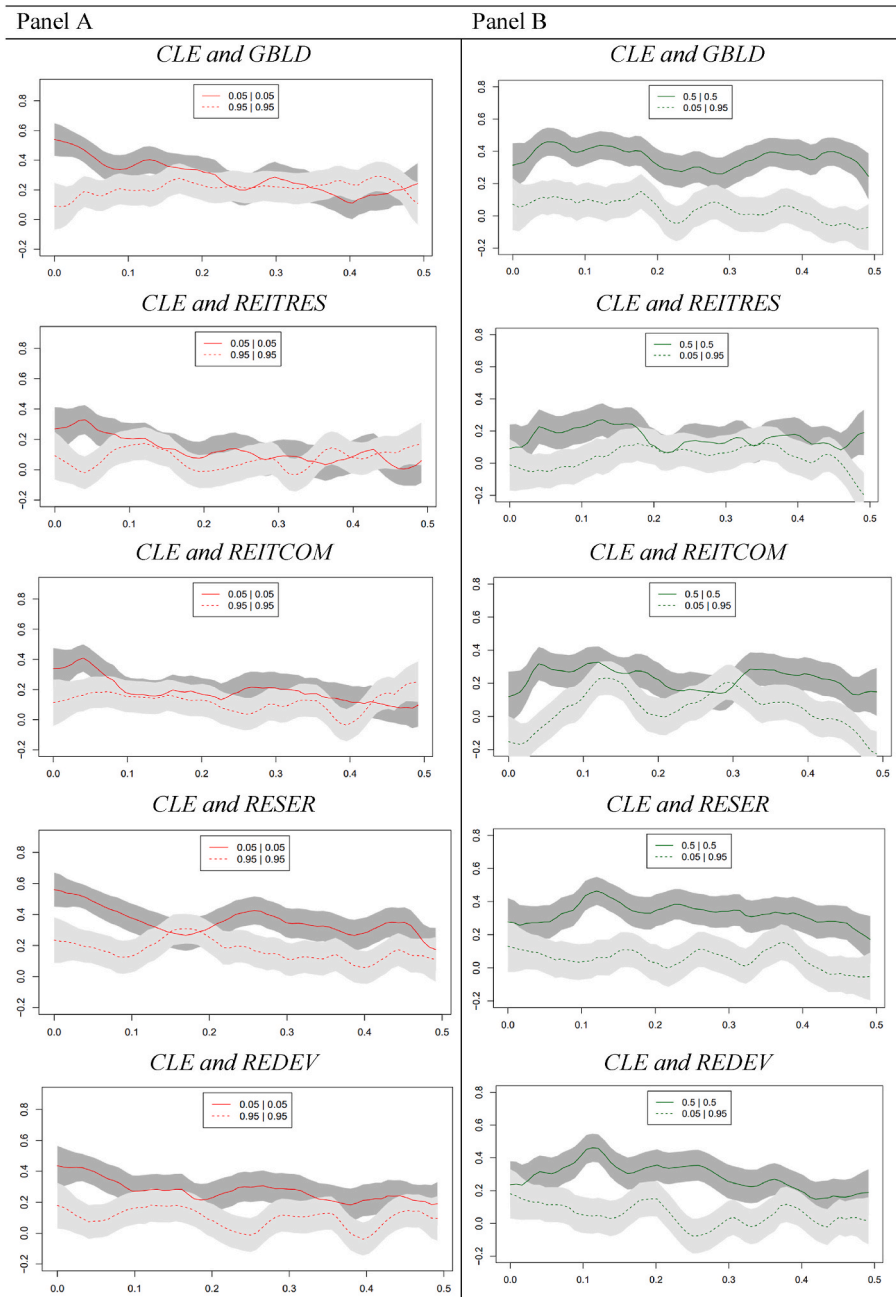
Therefore, the returns of GB seem to be more influenced by the real estate sector during boom rather than bust periods. One potential explanation is that during boom periods, real estate companies are more prone to make environmentally related investments for instance by issuing green bonds, which in the end might push the returns on the green bonds market. The increased correlation over time might reflect higher awareness of environmental related questions over time.

In general, the correlations in both lower and higher quantiles for most variable combinations vary over time. Our empirical results also indicate that the relationships between real estate assets and the sustainable portion of the stock market are time-varying in the tails. Another finding is that, when the returns are in the lower quantiles (i.e., direction from sustainable assets to the real estate market), the correlation increases over time. Thus, the influence of the sustainable assets on the returns of the real estate market intensifies during bust periods.

#### 4.4. Quantile coherency (QC) results

The results of the QC estimations are depicted in Figs. 11–14. Each figure is divided into two panels, A and B. In Panel A, we present the coherency when both of the series are in the same tail of their return distribution - i.e., left tail (the 0.05 quantile of both series, hereafter denoted as 0.05:0.05) and right tail (the 0.95 quantile of both series, hereafter denoted as 0.95:0.95). In Panel B, we present the results when both series are in the median of their distributions (0.5:0.5) and in opposite tails (0.05:0.95). If a high value of QC is found when both series are in their left tails, this indicates that the series are dependent when the returns are very low. A high value in the right tails indicates dependence when returns are very high.

We present the QC on the y-axis and the frequency on the x-axis. Given our daily dataset, the frequency represents the number of daily



**Fig. 13.** QC between CLE and real estate returns

Notes: the vertical axis represents the strength of the coherence and the horizontal axis refers to the frequency. Panel A (left-hand side) shows the coherence of the tails while Panel B (right-hand side) shows the coherence in the median and when the return series are in opposite tails. In both panels, the light grey color represents the 95% level confidence band for the dotted lines while the confidence band in dark grey relates to the filled lines.

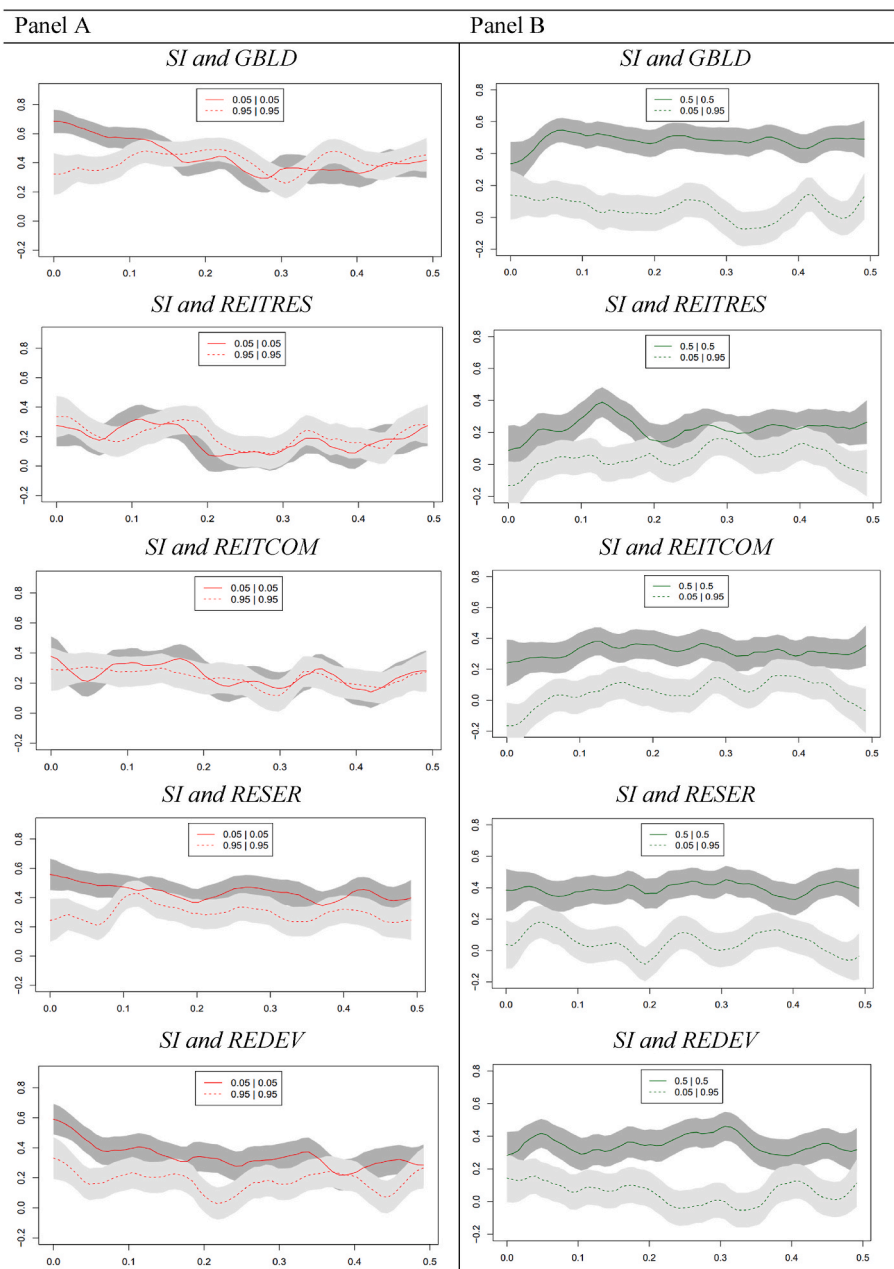
cycles. A daily cycle of 0.5 represents a two-day period, a 0.2 cycle refers to a weekly frequency, and 0.004 represents a yearly frequency. Hence, the x-axis spans from long-term periods on the left part of the axis to shorter-term periods on the right part.

In Panel A of Fig. 11, we observe the greatest quantile coherency when both return series are in their lowest quantile (0.05:0.05). Thus, the return of the real estate sector shows greater dependence with GB during extreme negative turmoil in comparison with when the returns are very high. In general, the dependence is stronger for short-term periods compared to middle or long-term ones. In this context, the frequencies might be interpreted as different investment strategies. Hence, these results suggest a higher connection between the sectors for investors involved in shorter-term strategies compared to longer-term.

From a portfolio perspective, this implies better diversification benefits for long-term rather than short-term investors.

For many other frequencies, both the low and high return cases, especially in medium-term periods, the QC is close to zero. However, the RESER shows high dependence with GB during medium-term periods. In the short run, the GBLD shows a greater QC with GB returns compared to other variables. Apart from that, there are no large differences in the strength of quantile coherency with GB returns related to the real estate sector.

Compared to the findings of Reboredo (2018), who did not find any tail-dependence between GB and the stock market, our results suggest tail-dependence when focusing specifically on the real estate segment of the stock market. The QC in Panel B of Fig. 11 mostly fluctuates around



**Fig. 14.** QC between SI and real estate returns

Notes: the vertical axis represents the strength of the coherence and the horizontal axis refers to the frequency. Panel A (left-hand side) shows the coherence of the tails while Panel B (right-hand side) shows the coherence in the median and when the return series are in opposite tails. In both panels, the light grey color represents the 95% level confidence band for the dotted lines while the confidence band in dark grey relates to the filled lines.

zero for both median quantiles (0.5:0.5) and the quantiles in the opposite tails (0.05:0.95). Weak coherency is, however, found between the returns of GB with the median quantiles of REITCOM and GBLD in the medium-term periods. In Panel A of Fig. 12, we observe high QC between ESG and real estate in the long term when the returns are very low (0.05:0.05). Compared to GB (Fig. 11), the coherency is considerably larger across frequencies, both when the returns of the series are low and high.

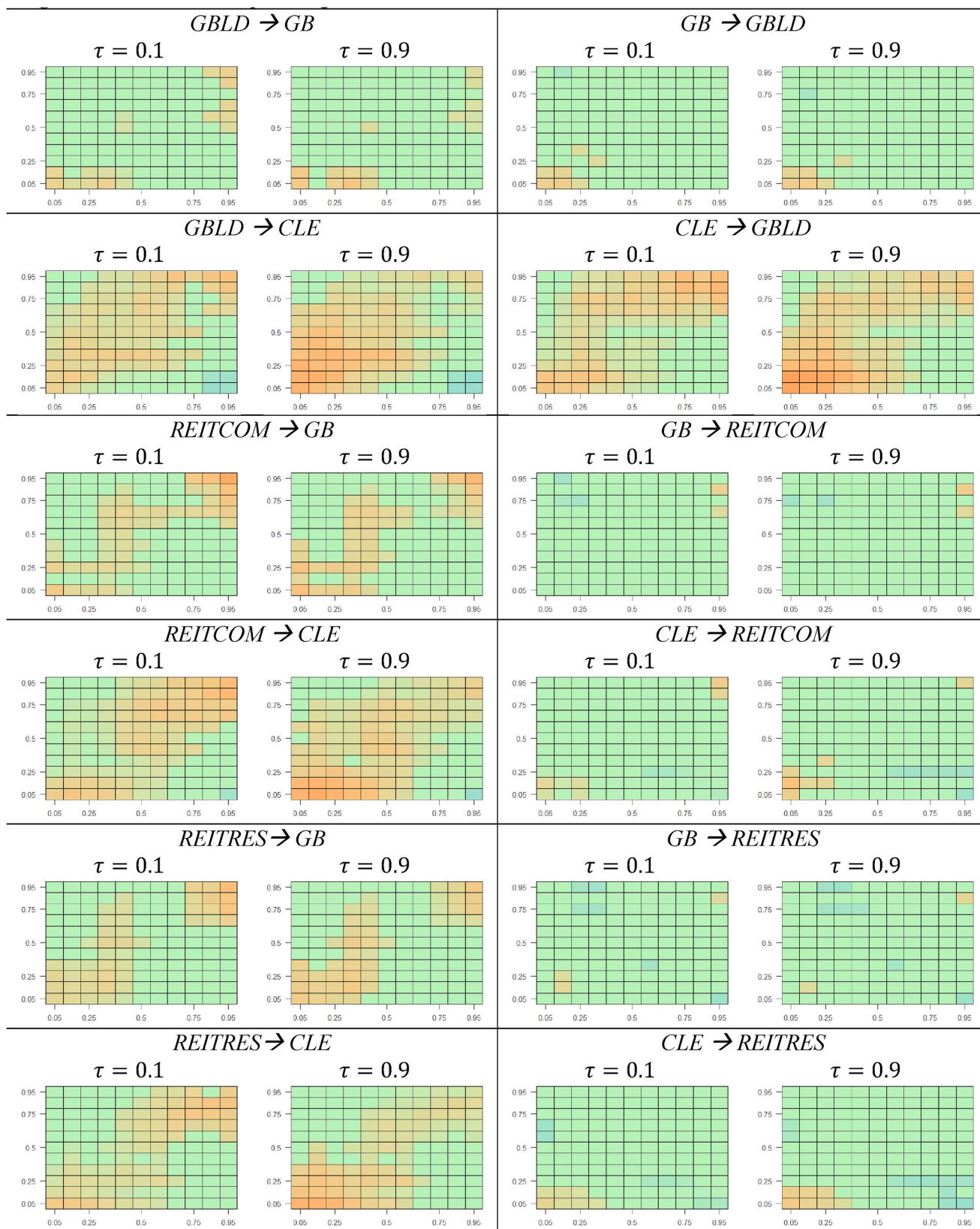
Compared to other real estate indices, returns of the REIT indices seem to be less dependent with the ESG across most frequencies. In Panel B of Fig. 12, we observe high QC when the returns are in their median quantiles, while weak to no dependence when they are in opposite tails. The coherency is, however, weaker for REITRES.

The QC of real estate returns and CLE, depicted in panel A of Fig. 13,

shows that coherency is greater than the results of GB (Fig. 11) but lower than for the real estate sector with ESG (Fig. 12). While Ivarsson Lundgren et al. (2018) find high dependence for clean energy with the overall stock market, we find high coherency for the real estate part of the market when the returns are very low at higher-term frequency. In short-term frequencies, the coherency is lower for REIT returns.

The QC of real estate indices and SI, depicted in Fig. 14, shows that the dependence in the left tails is, overall, very high in long-term frequencies while weaker for REIT indices. In Panel B of Fig. 14, we observe some dependence in the median for medium-term frequencies but low to no dependence when the returns are in opposite tails. The QC in the short-term frequencies is weaker but follows the same pattern.

Compared to the results for CLE, we observe the highest dependence for the GBLD. The coherence in the right tail (0.95:0.95) is, in general,



**Fig. 15.** Partial cross-quantilogram for selected variables

Notes: The vertical axis is the quantiles of the variable on the left-hand side of the arrow while the horizontal axis is the quantiles of the right-hand side variable. The arrow shows the direction of the correlation. The green color is displayed for quantile-combinations where the Box-Ljung test statistic is not significant while the red and blue colors display significant positive and negative correlations, respectively. We use a lag length of one in the estimations.

**Table 3**  
Quantile regressions.

Panel A. Real estate (RE) to sustainable asset returns										
RE → GB	RE → GB					RE → ESG				
	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9
GBLD	0.060 <sup>b</sup>	0.035 <sup>b</sup>	0.020	-0.003	0.007	0.225 <sup>b</sup>	0.089 <sup>c</sup>	0.008	0.015	-0.005
REDEV	0.042 <sup>c</sup>	0.020	0.008	0.009	0.030	0.055	0.033	0.018	0.005	0.012
RESER	0.046 <sup>b</sup>	0.022 <sup>c</sup>	0.013	0.013	0.039 <sup>b</sup>	0.068	0.012	0.005	0.005	0.044
REITCOM	0.061 <sup>a</sup>	0.044 <sup>a</sup>	0.029 <sup>b</sup>	0.024 <sup>c</sup>	0.043 <sup>b</sup>	-0.041	-0.047 <sup>c</sup>	-0.003	0.025	0.014
REITRES	0.064 <sup>a</sup>	0.039 <sup>a</sup>	0.017	0.022 <sup>b</sup>	0.041 <sup>b</sup>	-0.051	-0.053 <sup>b</sup>	-0.001	0.016	0.001
RE → CLE	RE → CLE					RE → SI				
	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9
GBLD	0.248 <sup>b</sup>	0.101 <sup>c</sup>	0.032	-0.061	-0.052	0.150 <sup>b</sup>	0.063	0.005	-0.042	-0.035
REDEV	0.106 <sup>c</sup>	0.043	0.050 <sup>b</sup>	0.014	-0.008	0.064 <sup>c</sup>	0.030	0.018	0.010	0.014
RESER	0.209 <sup>a</sup>	0.083 <sup>a</sup>	0.036	0.042	0.044	0.065	0.027	0.004	0.020	0.015
REITCOM	0.045	0.023	0.031	0.040	-0.036	-0.022	-0.019	0.011	0.027	0.025
REITRES	0.031	0.004	0.035	0.008	-0.031	-0.019	-0.033	0.006	0.000	0.02
Panel B. Sustainable asset to real estate (RE) returns										
GB → RE	GB → RE					ESG → RE				
	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9
GBLD	0.027	0.081	0.068	0.027	0.036	0.14	-0.085	-0.131	-0.117	-0.139
REDEV	0.076	0.209	-0.007	0.112	0.028	0.104	0.029	0.042	-0.235	-0.189
RESER	0.262	0.165	0.127	0.168	0.04	0.266	-0.024	-0.39 <sup>b</sup>	-0.371 <sup>b</sup>	-0.262
REITCOM	-0.067	-0.155 <sup>c</sup>	-0.001	-0.102	-0.01	-0.058	-0.097	-0.111	-0.188	-0.204
REITRES	-0.006	-0.039	-0.116	-0.159	-0.005	-0.181	-0.100	-0.026	-0.094	-0.283
CLE → RE	CLE → RE					SI → RE				
	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9	τ = 0.1	τ = 0.25	τ = 0.5	τ = 0.75	τ = 0.9
GBLD	0.060	0.042	0.025	0.002	0.070 <sup>c</sup>	0.018	-0.016	-0.090	-0.086 <sup>c</sup>	-0.171 <sup>b</sup>
REDEV	0.039	0.117 <sup>a</sup>	0.01	0.007	-0.028	0.047	0.013	-0.019	-0.097	-0.146
RESER	0.197 <sup>a</sup>	0.063	0.011	-0.007	-0.016	0.12	-0.01	-0.079	-0.052	-0.104
REITCOM	0.005	0.023	0.026	0.042	0.042	-0.247 <sup>b</sup>	-0.149 <sup>b</sup>	-0.122 <sup>b</sup>	-0.104	-0.099
REITRES	-0.016	0.008	0.018	0.033	0.008	-0.287 <sup>b</sup>	-0.132 <sup>c</sup>	-0.074	-0.182 <sup>b</sup>	-0.11

Notes.  
<sup>a</sup> if p < 0.01.  
<sup>b</sup> if p < 0.05.  
<sup>c</sup> if p < 0.1.

weak for most real estate indices. This suggests that the dependence is commonly more pronounced during turbulent times, especially in longer-term frequencies. Interestingly, the dependence is also stronger when the returns are in the median quantiles (Panel B of Fig. 14) compared to boom periods (0.95:0.95), across most frequencies.

**5. Robustness checks**

Our purpose in this paper is to study the co-movement between different assets, and we have thus only focused on two assets at a time. In two different robustness checks, we examine whether the relationships still exist after controlling for a state factor. Firstly, we estimate our quantile heatmaps with the partial cross-quantilogram (pCQC), using a lag length of 1. This method allows us to estimate quantile correlations between two assets while controlling for a state variable z, see Han et al. (2016). We control for the general return of a broad stock index to determine if the correlations between our variables are influenced by factors affecting the overall market. Hence, we include the S&P 500 composite (MKT) as the state variable. A limitation is that we must control for a specific quantile of the control variable. Therefore, we experiment by controlling for very low (τ = 0.1) and very high (τ = 0.9) quantiles of the S&P 500 composite returns.

To save space, we choose to focus only on three real estate series and two different series for sustainable investments. The results of this robustness estimation are shown in Fig. 15. From this figure, we can

observe that the correlations, as compared to the corresponding results in section 4.2, weaken considerably in the bottom left corner when we control for low market returns (τ<sub>MKT</sub> = 0.1). The correlations do, however, not disappear completely. Unlike the results with CLE, the relationships between the real estate market and GB do not weaken as notably. As for the results when we control for high market returns (τ<sub>MKT</sub> = 0.9), we observe as before, that the correlations weaken, but this time in the upper right corner. However, the correlations still remain significant to some extent.

For the second robustness check, we estimate a set of quantile regressions that include the lagged returns of the S&P 500 composite as a control variable. The results from these regressions are displayed in Table 3. In panel A, the returns of each of the four sustainable assets (GB, ESG, CLE, SI) are used as the dependent variable, regressed on the lagged returns of a real estate series and the market return. Hence, we estimate the following regressions for each selected quantile τ:

$$Q_{SustInv_t}(\tau|x) = \alpha(\tau) + \beta(\tau)RE_{t-1} + \varphi(\tau)MKT_{t-1} + \varepsilon(\tau)_t \tag{8}$$

Since we include only one real estate asset at a time, Panel A consists of 100 separate regressions (5 real estate assets, 5 quantiles, and 4 sustainable assets). Thus, in Panel A of Table 3, the coefficients that are shown are those from the real estate assets, β(τ) of Equation (8). In Panel B, we use the returns of each of the real estate assets as the dependent variable, and the lagged returns of the sustainable assets and the market as independent variables. Thus, for each quantile τ, we estimate:

$$Q_{RE_i}(\tau|x) = \alpha(\tau) + \beta(\tau)SusInv_{t-1} + \varphi(\tau)MKT_{t-1} + \varepsilon(\tau)_t \quad (9)$$

Thus, in Panel B of Table 3, the coefficients that are shown are those from the sustainable assets,  $\beta(\tau)$  of Equation (9).

From the quantile regressions, we observe three main findings. In Panel A, we find that the lagged returns from the real estate indices significantly impact GB, especially in the lower quantiles. This suggests that the real estate indices precede, or spillover, to GB, but GB does not have a similar effect on the real estate market (see Panel B). Secondly, we find that the lagged returns from the real estate indices exhibit more significant relationships with CLE (i.e., clean energy) rather than with ESG or SI. Finally, from Panel B, we also find that the lagged returns of SI show significant relationships with parts of the real estate sector (REITCOM and REITRES) in the lower quantiles.

## 6. Conclusion

Despite the known linkages between real estate and clean energy assets, studies exploring co-movements or dependence between them are still scarce. Such information could be relevant in terms of risk management, investment diversification, and public policy purposes. In the present study, we investigate the dependence between the real estate sector and sustainable assets. To capture the non-linear dependence over both time and frequency, we apply the recently proposed CQ and QC methods on real estate and sustainable assets time series data.

Our empirical results indicate unidirectional dependence from the real estate sector to most sustainable assets, in both tails and during normal market conditions, but bi-directional dependence in lower quantiles - i.e., during turbulent times. This indicates that the real estate sector is more influential in predicting returns of sustainable assets than the opposite. However, such a dependence structure varies over time, both in terms of frequency and between subsectors of the real estate sector.

We also observe that the influence of sustainable assets on the real estate market during bust periods has increased over time. Another interesting finding from the recursive window estimations is that when the Covid-19 period is included in our sample period (i.e., we estimate the CQC with all data), we find that GB is tail-dependent on real estate assets, both during boom-and-bust periods. However, if we use a shorter window, thus excluding such unusual period, then we find greater dependency with the real estate sector during booms periods. Therefore, the dependence in the left tail might be explained by a widespread downturn, leading to a positive correlation between asset classes.

Compared to other sustainable assets, we also find that the return of GB is less dependent on the returns of the real estate sector. For companies involved in green building (GBLD), we find a bi-directional dependence with most sustainable assets in a considerable part of our CQ heatmaps. This suggests that green building may be more connected to the real estate market during most market conditions compared to the rest of the real estate sector, as both sectors are mutually influencing each other.

From a portfolio perspective, our results may be relevant to investors with real estate and/or sustainable assets in their holdings. The tail-dependence found in lower quantiles means that ESG or CLE assets do not improve diversification for real estate investors, or vice versa, during periods of turbulence. However, given the variation across frequencies, the diversification opportunities are conditional on the investment strategy.

## CRedit authorship contribution statement

**Michel Ferreira Cardia Haddad:** Writing – review & editing, Writing – original draft, Project administration, Formal analysis. **Bo Sjö:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **David Stenvall:** Writing – original draft, Methodology, Formal analysis, Data curation. **Gazi Salah Uddin:**

Writing – original draft, Supervision, Resources, Project administration, Conceptualization. **Anupam Dutta:** Writing – original draft, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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