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A measure of quantile-on-quantile connectedness for the US treasury yield curve spread, the US Dollar, and gold price

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ABSTRACT

This study applies the Quantile-on-Quantile Connectedness approach to analyze quantile spillovers between the US yield curve spread (10-year vs. 2-year Treasury yields), the US dollar, and gold price from 2 January 2000 to 31 July 2023, covering the COVID-19 pandemic. Our results show that inversely related quantiles demonstrate significantly higher average total connectedness than directly related quantiles among these variables. Additionally, we found that this quantile-based connectedness fluctuates over time, suggesting a dynamic and varied relationship between the US yield spread, the US dollar, and gold prices throughout the period studied.

1. Introduction

This study adopts the Quantile-on-Quantile connectedness methodology to dissect the nature of quantile spillovers—both direct and inverse—among critical financial indicators: the US yield curve spread (precisely, the difference between the 10-year and 2-year US Treasury yields), the US dollar, and gold price during the COVID-19 pandemic, spanning from January 2, 2000, to July 31, 2023. Investigating the quantile-on-quantile connectedness of these financial metrics throughout the pandemic is vital for multiple reasons: it offers profound insights into the intricacies of financial market dynamics, bolsters risk management frameworks, and provides valuable guidance for economic policymaking.

In the face of the COVID-19 pandemic's unprecedented volatility and uncertainty across global financial markets, this research employs a Quantile-on-Quantile connectedness approach to scrutinize how extreme market events—both adverse and favorable—impact market stability and investor behavior. By analyzing the interconnectedness across different quantiles of key financial metrics—the US yield curve spread, the US dollar, and gold price—this study sheds light on market stress and resilience mechanisms,

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revealing how markets adapt to extreme conditions.

Exploring quantile-based spillovers among the US yield curve spread, the US dollar, and gold price is crucial for investors and financial institutions. This analysis identifies the conditions under which these assets demonstrate varying levels of interconnectedness, equipping stakeholders with critical insights for developing risk mitigation strategies amidst market volatility. This is particularly significant given the role of the yield curve spread as an economic predictor and the traditional view of the dollar and gold as safe havens during uncertain times. Understanding the shifts in these relationships during the COVID-19 crisis provides policymakers with essential feedback on the impact of their interventions, informing future policy adjustments to foster economic stability and recovery.

This study challenges conventional analyses that often assume linear relationships between financial variables by delving into the non-linear dynamics and asymmetries in these relationships through the Quantile-on-Quantile methodology. This innovative approach grants a nuanced understanding of how various market segments respond under different scenarios, underscoring the complexity of financial market interactions, particularly in times of stress.

The research also uncovers that quantile-based total connectedness fluctuates over time, highlighting the dynamic nature of these relationships across varying market conditions (Sims and Zhou, 2015). Such temporal insights are indispensable for grasping the evolution of market interconnectedness, especially during periods of economic uncertainty and recovery, and they pave the way for the formulation of dynamic investment strategies (Diebold & Yilmaz, 2009; Diebold and Yılmaz, 2012).

The insights derived from this study are invaluable for policymakers, assisting in crafting targeted interventions that stabilize specific market segments with minimal collateral effects. For investors, the findings deepen their understanding of market dynamics, informing more strategic decisions regarding asset allocation, hedging, and diversification.

Ultimately, this investigation into the Quantile-on-Quantile connectedness among the US yield curve spread, the US dollar, and gold price during the COVID-19 pandemic not only deepens our comprehension of financial market dynamics under duress but also significantly enhances risk management, policy development, and investment strategy refinement. This underscores the study's aim to elucidate the complex interactions among vital financial indicators in times of turmoil.

This study is critical because it provides a nuanced understanding of the complex and non-linear dynamics that govern financial markets, especially during periods of significant stress like the COVID-19 pandemic (Zhang et al., 2020). Traditional linear models often need to catch up on capturing the true nature of these relationships, particularly under extreme conditions. By employing a Quantile-on-Quantile connectedness approach, this study goes beyond conventional methods to uncover the varying degrees of interconnectedness across different market states.

The need to conduct this study is underscored by the heightened volatility and uncertainty that characterized global financial markets during the pandemic. Understanding how critical financial indicators interact under such conditions is essential for developing robust risk management strategies and effective economic policies. This study contributes to the literature by providing empirical evidence on the quantile-based spillovers among vital financial metrics, offering insights that are not only timely but also relevant for future market disruptions (Ji et al. 2020).

The novelty of this study lies in its methodological approach. The Quantile-on-Quantile connectedness methodology allows for a more detailed examination of how different quantiles of financial variables interact with each other. This approach reveals the presence of asymmetries and non-linearities in these relationships, providing a richer and more accurate depiction of market dynamics.

The main findings of this study highlight that the interconnectedness between the US yield curve spread, the US dollar, and gold price varies significantly across different quantiles and over time. These variations reflect the changing nature of market stress and resilience, offering valuable insights into how markets respond to extreme conditions. Such findings are crucial for investors and policymakers, as they provide a basis for developing more adaptive and practical strategies (Hong & Li, 2015).

This study has significant policy implications. For policymakers, understanding the dynamic nature of market interconnectedness can inform the design of targeted interventions that stabilize specific market segments without causing unintended consequences elsewhere. For investors, the insights gained from this study can enhance decision-making processes related to asset allocation, hedging, and diversification, particularly in volatile market environments (Adrian & Liang, 2018).

This study's generalizability extends beyond the specific period of the COVID-19 pandemic. The methodology and insights can be applied to other periods of market stress, making this research relevant for understanding financial market dynamics in various contexts. This study addresses the critical problem of how financial markets behave under extreme conditions, providing a framework for analyzing similar scenarios in the future.

In summary, this study advances our understanding of financial market dynamics during unprecedented volatility and offers practical implications for risk management and policy formulation (Diebold & Yilmaz, 2009). By exploring the complex interactions among the US yield curve spread, the US dollar, and gold price, this research contributes to a deeper and more comprehensive understanding of market behavior in times of crisis.

The paper is structured as follows: Section II reviews the existing literature, Section III describes the data utilized in this study, Section IV outlines the methodology, Section V presents the empirical findings and discusses policy implications, and Section VI concludes the study.

2. Review of literature

Some consider the yield curve spread to be a valuable tool for predicting recessions in the United States. It has been observed in several studies that a negative yield spread, or an inverted yield curve, has managed to precede every U.S. recession in the past 60 years. Some have attempted to utilize machine learning algorithms to identify the best maturity pair and coefficients for predicting recessions using the yield curve spread. However, these approaches have yet to significantly improve prediction accuracy due to

estimation error. Furthermore, a hidden Markov model has been shown to effectively predict recessions in the U.S. by incorporating the yield spread and other financial indicators. In conclusion, the yield curve spread has displayed strong predictive power for future economic activity and may serve as a valuable indicator for investors and policymakers (An et al., 2020; Bhanja and Dar, 2023a,b; Candila et al., 2021; Chai et al., 2021).

The methodology of Quantile-on-Quantile connectedness is used in several studies to analyze the interdependence and spillovers among financial variables (Ren et al., 2022; Raza et al., 2022; Gabauer & Stenfors, 2024; Jiang et al., 2022). Within the framework of the US systemic cycle of capital accumulation, the role of the dominant currency is assigned to the US dollar. This can impact gold and the spread of the USA yield curve. Thus, one critical step is displacing the dominant global currency from domestic and foreign markets (Yao & Alexiou, 2022; Yun et al., 2023; Zagaglia & Marzo, 2022).

Many researchers observed the link between directly and inversely related quantiles affecting the interconnectedness of the yield curve spread, gold prices, and the dollar calls for refined monetary policy formulation (Abdullah et al., 2023; Aharon et al., 2021). The assumption of the loss of the role of the world currency by the US dollar is high. There is a long-term trend towards weakening the dollar's position in the global economy. Two things inevitably happen at some point: first, other countries express dissatisfaction and try to develop alternative systems. BRICS countries implement a system of bilateral trade agreements in which goods are exchanged for one another without the use of the dollar. Another crisis may be required to achieve such tectonic shifts in the global financial system as the displacement of the dominant world currency. As practice has shown in 2022, qualitative changes in the international monetary system were triggered by extraordinary events. A future crisis may happen against the background of unpleasant surprises that we observed in Germany, Japan, and Italy in the twentieth century (Gomes et al., 2023; Gomis-Porqueras et al., 2022; He & Krishnamurthy, 2020; He et al., 2022; Houcine et al., 2020).

The future role of the dollar, gold, and US treasures with a shift in the center of gravity of the world economy towards the largest developing countries, including China. China may become the largest economy after the United States by 2030, and the share of developing countries in global GDP will exceed 50 %. At the same time, the researchers assume any scenarios for spillovers between the USA yield curve spread, gold, and USD (Mikhaylov et al., 2023; Prasad et al., 2022). The role of the US dollar and gold is decreasing, and the yuan's internationalization is slowing down. To do this, the US authorities must contain the budget deficit. The significant inertia of the processes in changing the status of reserve currencies also speaks in favor of this scenario (Kwon, 2020; Liu, 2021).

Some researchers have discerned correlations and interconnections among various financial variables at different quantiles, showcasing the intricate relationships within the finance realm. This analysis delves into the nuanced interactions between different aspects of the economic landscape, shedding light on how changes in one variable can impact others across various levels of the distribution (Malliaris & Malliaris, 2020; Mensi et al., 2022; Mikhaylov, 2023).

It loses its position and is replaced by a basket of three currencies—the dollar, the euro, and the yuan. The condition for its implementation should be the acceleration of the yuan's internationalization and transformation into a critical regional currency in Asia. The starting point for building such a system would be gold or the SDR basket (Idilbi-Bayaa & Qadan, 2021; Jalkh & Bouri, 2024; Jareño et al., 2020).

Table 1
Summary of previous literature.

Study	Methodology	Key Findings	Implications
An et al. (2020)	Machine learning	Yield curve spread predicts recessions but with estimation errors	Limited improvement in prediction accuracy
An et al. (2020)	GDP forecasts analysis	Forecasts inaccurate; slow revisions in recessions and booms	Forecasts unreliable; slow adjustments due to data/model limitations
Bhanja & Dar (2023)	Hidden Markov model	Yield spread and other indicators predict US recessions effectively	Valuable for economic forecasting and policy formulation
Ren et al. (2022)	Quantile-on-Quantile connectedness	Interdependence and spillovers among financial variables	Highlights non-linear relationships in financial markets
Yao & Alexiou (2022)	Systemic cycle analysis	Role of US dollar impacts gold and yield curve spread	Insights into currency dominance and market dynamics
Abdullah et al. (2023)	Quantile regression	Direct and inverse quantile spillovers affect interconnectedness	Informs refined monetary policy formulation
Gomes et al. (2023)	Historical analysis	Future crisis could shift global financial system dynamics	Potential for displacement of dominant world currency
Mikhaylov et al. (2023)	Scenario analysis	Future role of USD, gold, and US treasures with economic shifts towards developing countries	Important for understanding global economic power shifts
Idilbi-Bayaa & Qadan (2021)	Currency basket analysis	Potential replacement of USD by a basket of currencies	Significance for international monetary system and reserve currencies
Saqib et al. (2021)	Fiscal analysis	Decline in non-resident demand for US treasuries and national debt implications	Critical for understanding fiscal policy and debt management
Umar et al. (2022)	Political factors analysis	Political factors causing the reduction in dollar circulation	Highlights the impact of political stability on financial variables
Ren & Li (2022)	QQ regression	Financial stress asymmetrically affects precious metals; safe haven only in bull markets. Structural changes post-global financial crisis.	Precious metals hedge in bull markets; ineffective during high stress.
Bhanja & Dar (2023)	Hidden Markov model	The yield curve spread best single predictor	Yield curve spread remains the dominant recession predictor

The character sharply narrows the financial base for servicing the US national debt. The consequence may be a drop in the demand of non-residents for US treasuries, and the state will be forced to resort to emissions. Note, however, that in 2020, such statements were premature. The share of non-residents in the Fed's liabilities has declined since 2008, and the national debt has been proliferating (Saqib et al., 2021; Triki & Maatoug, 2021).

While this specific period offers a distinct and unparalleled chance to analyze the intricate workings of markets in the face of extreme circumstances, it is crucial to acknowledge that the outcomes derived from such analyses may not be readily applicable or transferable to more consistent and stable economic eras. At the same time, the reduction in dollar circulation in 2022 was caused by political factors, which led to a loss of faith in the stability of the dollar, US treasuries, and gold (Umar et al., 2022; Umar et al., 2022; Vides et al., 2021; Wang & Lee, 2022).

Despite the extensive research on the interconnectedness of financial variables, there still needs to be a gap in understanding the non-linear and asymmetric relationships among the US yield curve spread, the US dollar, and gold price, especially under extreme market conditions such as those witnessed during the COVID-19 pandemic This study aims to fill this gap by employing the Quantile-on-Quantile connectedness methodology to provide a more detailed and nuanced analysis of these relationships. The findings from this research will offer new insights into market dynamics and inform more effective risk management and policy strategies. Details about the previous studies are shown in Table 1.

3. Theoretical background of our study

The theoretical foundation of this study is rooted in the interconnectedness of financial markets and the advanced methodologies employed to analyze these relationships. The primary focus is understanding the quantile-on-quantile connectedness among the US yield curve spread, the US dollar, and gold prices, particularly during periods of economic stress such as the COVID-19 pandemic.

The concept of quantile-on-quantile connectedness extends traditional connectedness approaches by focusing on the interactions across different quantiles of the distributions of financial variables. This methodology, introduced by Gabauer and Stenfors (2024), builds on the quantile regression framework proposed by Koenker and Bassett (1978), which allows for the analysis of the relationships between variables at different points in their distributions rather than assuming a uniform effect across the entire distribution.

Quantile regression is instrumental in financial econometrics as it captures the heterogeneity in market behavior under different conditions, such as during periods of market stress or stability. The quantile-on-quantile approach further enhances this by examining how specific quantiles of one variable affect the quantiles of another variable, providing a more granular understanding of market dynamics.

The yield curve spread, precisely the difference between the yields on 10-year and 2-year US Treasury bonds, is a critical economic indicator. Historically, an inverted yield curve (where short-term rates are higher than long-term rates) has been a reliable predictor of economic recessions (Estrella and Mishkin, 1996). The yield curve spread reflects investor expectations about future interest rates and economic activity. During periods of economic uncertainty, such as the COVID-19 pandemic, the yield curve spread becomes particularly volatile, making its analysis crucial for understanding broader market dynamics.

The US dollar and gold prices are essential to the global financial system. The US dollar, the world's primary reserve currency, plays a significant role in international trade and finance. Many factors, including interest rates, inflation expectations, and geopolitical stability, influence its value. Gold, on the other hand, is traditionally viewed as a safe-haven asset. Investors flock to gold during economic uncertainty, which drives up its price. Understanding the interconnectedness between the US dollar and gold prices provides insights into investor behavior and market sentiment.

The interconnectedness of financial markets refers to the degree to which different financial variables influence each other. Traditional measures of connectedness, such as those developed by Diebold and Yılmaz (2012), focus on volatility spillovers among financial assets. However, these measures often assume linear relationships and do not capture the complexities of market dynamics under different conditions. The quantile-on-quantile connectedness approach addresses these limitations by allowing for the analysis of non-linear and asymmetric relationships.

Financial markets are inherently non-linear and characterized by periods of calm interspersed with extreme events. The presence of non-linear and asymmetric effects means that the relationships between financial variables can change depending on the market's state. For instance, the correlation between the US dollar and gold prices may differ during a financial crisis compared to a period of stability. This study captures these nuances by employing the quantile-on-quantile methodology, providing a more accurate depiction of market behavior.

The COVID-19 pandemic presents a unique context for analyzing financial market interconnectedness. The unprecedented economic disruption caused by the pandemic has led to significant volatility across all major financial markets. The study offers valuable insights into how extreme events impact market dynamics and investor behavior by examining the quantile-on-quantile connectedness among the US yield curve spread, the US dollar, and gold prices during this period.

The theoretical background of this study combines advanced econometric methodologies with a deep understanding of key financial indicators. By focusing on the quantile-on-quantile connectedness among the US yield curve spread, the US dollar, and gold prices, the study contributes to the broader literature on financial market dynamics, particularly under conditions of economic stress. This approach enhances our understanding of market interconnectedness and provides practical implications for risk management and policy formulation during periods of extreme market volatility.

4. Data

This study analyzes data on the US dollar, gold price, and the US yield curve spread between the 10-year and 2-year US Treasury yields (X102Y). This data, sourced from the Federal Reserve Economic Database (FRED), spans from January 2, 2000, to July 31, 2023, encompassing the COVID-19 pandemic period (refer to Figs. 1, 2, and 3).

Based on Figs. 1, 2, and 3, all data series were volatile and showed ARCH/GARCH errors.

Our statistical analysis, summarized in Table 2, reveals several key findings. Notably, the variance observed in the US yield spread curve (X102Y) series is more significant than that of the UA dollar and gold price series. Additionally, the data's skewness indicates that the US yield spread curve and gold price series are significantly left-skewed, whereas the US dollar series shows a significant right skew. Both the US dollar and the US yield curve spread series are identified as significantly platykurtic, and the gold price is determined as significantly leptokurtic, with all series deviating from a normal distribution, as confirmed by J-B normality tests.

Further examination confirms that all series exhibit significant autocorrelation. Fig. 4 serves as a visual representation of the comprehensive distribution patterns and interdependencies between the variables. Our examination has unearthed a noteworthy positive correlation between gold price (lgold) and the US dollar (lrej), along with a negative correlation between the US yield curve spread (X102Y) and the US dollar (lrej) and a negative correlation between the US yield curve spread (X102Y) and gold price (lgold). We have found a significant correlation between them. It's pertinent to note that the variables investigated possess non-normal distributions, which renders the results complicated. Our observation is bolstered by the outcomes from the Jarque-Bera test.

Fig. 4 shows the complex dynamics between the US dollar and the US yield curve spread, between the gold price and the US yield curve spread, and between the US dollar and gold price, highlighting their significant statistical properties and interactions during the study period.

5. Quantile_on_Quantile connectedness approach

Gabauer and Stenfors (2024) introduce the quantile-on-quantile connectedness approach as an advancement over the quantile connectedness framework proposed by Chatziantoniou et al. (2021). This novel methodology evaluates the interdependencies between different quantiles ($\tau_1, \tau_2, \ldots, \tau_K$) of two financial indicators: gold price and the US dollar, the US yield curve spread and the US dollar, and the US dollar and gold price. Specifically, it examines how a particular quantile (τ_1) of the US dollar's value influences a specific quantile (τ_2) of the US yield curve spread and vice versa. This approach is inspired by the Quantile-on-Quantile regression technique developed by Sim and Zhou (2015). Still, it extends its application into the domain of dynamic connectedness, a concept detailed by Diebold and Yılmaz (2012).

Our enhanced approach offers a significant advantage over the original quantile connectedness method by capturing the intricate dynamics between different quantiles across financial series. Unlike the original method, which assumes a uniform positive correlation across all series at a single quantile level, our method provides a nuanced analysis. It recognizes and quantifies the dynamics of spillover effects across various quantiles, emphasizing the importance of both the direction and magnitude of correlations.

Our empirical findings highlight the effectiveness of this approach, particularly in scenarios where financial series display negative correlations. In such instances, the Quantile-on-Quantile connectedness approach reveals a greater degree of inversely related total connectedness index than what is observed through the traditional quantile connectedness method. This emphasizes the crucial need to consider both the sign and magnitude of correlations to grasp the complex interdependencies in financial markets fully. For details about the Quantile-on-Quantile connectedness approach, see Gabauer and Stenfors (2024).

To delve into the Quantile-on-Quantile transmission mechanism between the US dollar and the US yield curve spread, as well as between the US dollar and gold price and between the gold price and the US yield curve spread, we will extend the quantile connectedness approach of Chatziantoniou et al. (2021). This extension allows us to account for how interdependencies vary across quantiles. To achieve this, we first introduce a QVAR(p) model that enables the estimation of dependencies at different quantiles, offering a more comprehensive understanding of financial market dynamics. The Quantile VAR model is defined as the follows:

$$x_t = \mu(\tau) + \sum_{j=1}^{p} B_j(\tau) x_{t-j} + u_t(\tau) \tag{1}$$

x_t and x_{t-j} are $K \times 1$ dimensional endogenous variable vectors, τ is a vector of quantiles which are between [0, 1], p stands for the lag length of the QVAR, $\mu(\tau)$ is a $K \times 1$ dimensional conditional mean vector,$B_j(\tau)$ is a $K \times K$ dimensional QVAR coefficient matrix, and $u_t(\tau)$ demonstrates a $K \times 1$ dimensional error vector with a $K \times K$ dimensional variance–covariance matrix, $H(\tau)$. In order to compute the generalized forecast error variance decomposition (GFEVD) proposed by Koop et al. (1996), the QVAR is transformed to a QVMA (Quantile Vector Moving Average) using the Wold representation theorem: $x_t = \mu(\tau) + \sum_{j=1}^{p} B_j(\tau) x_{t-j} + u_t(\tau) = \mu(\tau) + \sum_{i=0}^{\infty} A_i(\tau) u_{t-i}(\tau)$. Subsequently, the F-step ahead GFEVD represents the impact a shock in series j has on series i, which is formulated as follows:

$$\phi^{g}_{i \leftarrow j,\tau}(F) = \frac{\sum_{f=0}^{F-1} (e_i' A_f(\tau) H(\tau) e_j)^2}{H_{ii}(\tau) \sum_{f=0}^{F-1} (e_i' A_f(\tau) H(\tau) A_f(\tau)' e_i)} \quad gSOT_{i \leftarrow j,\tau}(F) = \frac{\varnothing^{g}_{i \leftarrow j,\tau}(F)}{\sum_{j=1}^{k} \varnothing^{g}_{i \leftarrow j,\tau}(F)} \tag{2}$$

where e_i is a $K \times 1$ dimensional zero vector with unity on its i th position. As the row sum of $\varnothing^{gen}_{i \leftarrow j,\tau}$ is not equal to unity, Diebold and

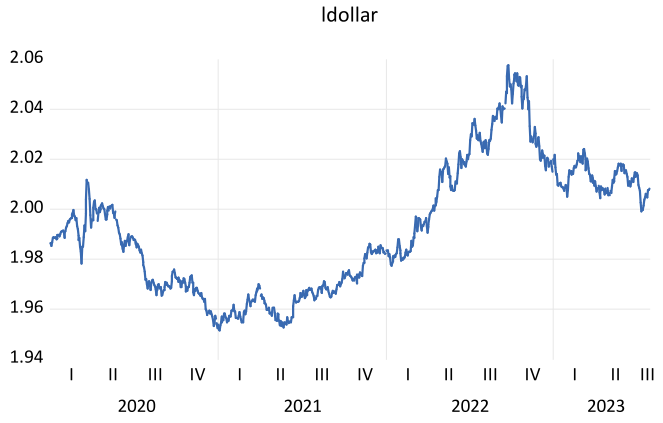

Fig. 1. The US Dollar in Log form.

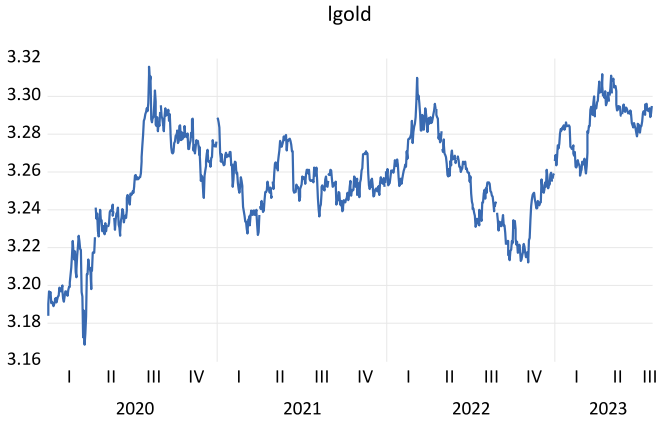

Fig. 2. Gold Price in Log form.

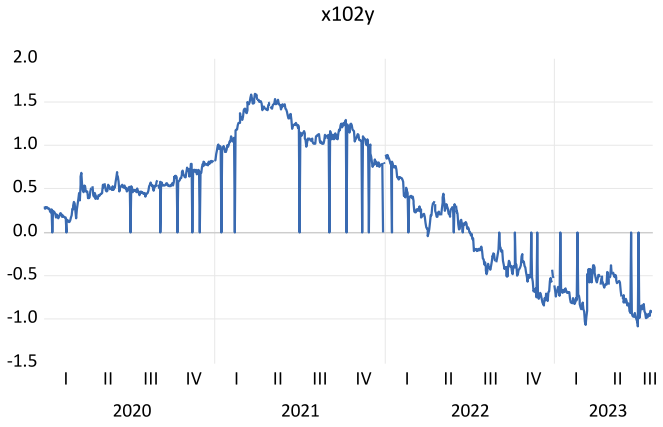

Fig. 3. Treasury Yield Spread (10Y-2Y) in the USA.

Yılmaz (2012) suggested normalizing $\varnothing^{gen}_{i\leftarrow j,\tau}(H)$ by dividing it by the row sum to obtain the scaled GFEVD, $gSOT_{i\leftarrow j,\tau}(F)$.

The scaled GFEVD is at the heart of the connectedness approach and is used to compute the total directional connectedness TO (FROM) others. While the TO total directional connectedness illustrates the effect series *i* has on all others, the FROM total directional connectedness illustrates the impact all series have on series *i*. These connectedness measures can be calculated as follows,

Table 2
Statistic description.

	GOLD	REJ	X102Y
Mean	3.257524	2.073501	0.332922
Median	3.258146	2.053117	0.440000
Maximum	3.315372	2.176482	1.590000
Minimum	3.168571	2.010130	−1.080000
Std. Dev.	0.026758	0.049244	0.704553
Skewness	−0.533214	0.528965	−0.188257
Kurtosis	3.139199	1.687969	1.994133
Jarque-Bera	43.37418***	106.5241***	43.25742***

*, **, and *** are significant at the levels of 10%, 5%, and 1%, respectively.

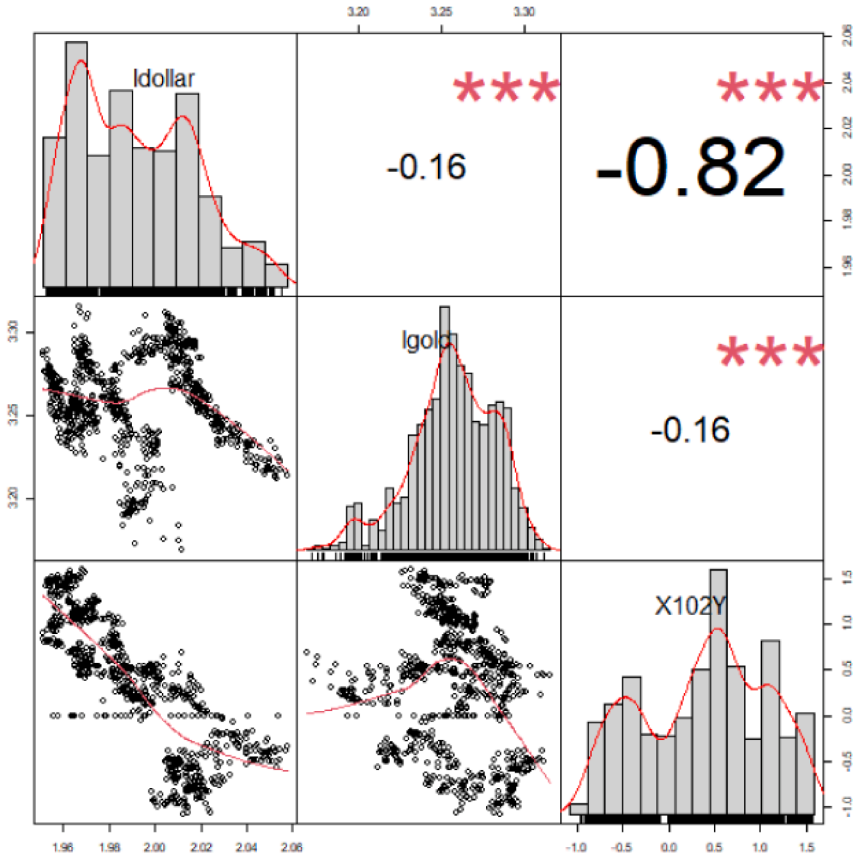

Fig. 4. Plots of Distribution and the Pair-wise Correlations of the Variables. *** Illustrates a 1 % significance level. Where Y = ldollar (the Dollar), X = the gold (Gold Price), X102Y = Yield Curve Spread (10Y-2Y).

$$S_{i\rightarrow\bullet,\tau}^{gen.to} = \sum_{k=1,i\neq j}^{k} gSOT_{k\leftarrow i,\tau} \tag{3}$$

$$S_{i\leftarrow\bullet,\tau}^{gen.from} = \sum_{k=1,i\neq j}^{k} gSOT_{i\leftarrow k,\tau} \tag{4}$$

The difference between the TO and FROM total directional connectedness results in the NET total directional connectedness of series i,

$$S_{i,\tau}^{gen.net} = S_{i\rightarrow\cdot,\tau}^{gen.to} - S_{i\leftarrow\bullet,\tau}^{gen.from} \tag{5}$$

where $S_{i,\tau}^{gen.net} > 0$ ($S_{i,\tau}^{gen.net} < 0$) indicates that series i is influencing all other series more (less) than being influenced by them and is therefore considered as a net transmitter (receiver) of shocks.

Finally, the adjusted total connectedness index (TCI) of Chatziantoniou et al. (2021), which ranges between [0, 1] is computed by,

$$\mathrm{TCI}_{\tau}(F) = \frac{K}{K-1}\sum_{K=1}^{K} S_{k\leftarrow\bullet,\tau}^{gen,from} \equiv \frac{K}{K-1}\sum_{K=1}^{K} S_{k\leftarrow\cdot,\tau}^{gen,to} \tag{6}$$

This measure computes the degree of network interconnectedness. Hence, the higher the TCI, the higher the market risk.[1]

6. Empirical results and policy implications

Given the initial series' non-stationarity, as evidenced by several unit-root tests detailed in Table 3, our analysis proceeds with the first-differenced series. This methodological choice enables us to analyze changes in the US dollar, gold prices, and the US yield curve spread in terms of basis points.

1 **Empirical findings**

In our research, we apply the Quantile-on-Quantile Connectedness methodology, adopting a 200-day rolling window approach for the Quantile Vector Autoregression (QVAR) model. This model is configured with a single lag and forecasts made 20 steps ahead, aligning with the methodology described by Chatziantoniou et al. (2021). Our analysis begins with examining averaged connectedness measures, delving into the intricacies of connectedness among directly and inversely related quantiles to understand their dynamic interplay.

2 **Findings on financial relationships**

Figs. 5, 8, and 11 showcase the average dynamic total connectedness indices for the relationship between gold prices and the US dollar. Our results indicate that inversely related quantiles, ranging from [τ1 = 10 %, τ2 = 95 %] to [τ1 = 90 %, τ2 = 25 %], have weaker connectedness compared to directly related quantiles ([τ1 = 10 %, τ2 = 10 %] to [τ1 = 95 %, τ2 = 95 %]). However, exceptions for the pairs ([τ1 = 10 %, τ2 = 10 %], [τ1 = 75 %, τ2 = 90 %], and [τ1 = 95 %, τ2 = 95 %]) show that directly related quantiles can also exhibit pronounced connectedness in certain instances.

A similar pattern is observed in the interaction between the US yield curve spread and the US dollar, where inversely related quantiles ([τ1 = 5 %, τ2 = 95 %], [τ1 = 20 %, τ2 = 90 %], [τ1 = 30 %, τ2 = 80 %], and [τ1 = 45 %, τ2 = 60 %]) show more vital connectedness than directly related ones ([τ1 = 5 %, τ2 = 5 %] to [τ1 = 95 %, τ2 = 95 %]). This mirrored pattern in both financial relationships suggested a consistent trend in the dynamics of these variables across various quantile pairs, highlighting the nuanced and varied nature of their interconnectedness.

The analysis reveals a notable trend: inversely related quantile pairs ([τ1 = 5 %, τ2 = 95 %], [τ1 = 60 %, τ2 = 45 %], and [τ1 = 75 %, τ2 = 30 %]) demonstrate more substantial connectedness compared to directly related quantile pairs ([τ1 = 5 %, τ2 = 5 %] through to [τ1 = 95 %, τ2 = 95 %]). However, deviations from this pattern are observed in the quantile pairs ([τ1 = 80 %, τ2 = 80 %] and [τ1 = 95 %, τ2 = 95 %]), where directly related quantiles show more vital connectedness than their inversely associated counterparts.

3 **Implications of findings**

These patterns suggest a general trend where inversely related quantiles exhibit stronger connections across the examined financial relationships. Nonetheless, specific exceptions highlight these interactions' complexity and nuanced nature, indicating that the relationship between the US yield curve spread and gold price is not uniformly predictable but varies significantly under different conditions.

Figs. 6, 9, and 12 delve into the Quantile-on-Quantile total directional connectedness, shedding light on the complex dynamics between the US dollar, gold prices, and the US yield curve spread across diverse quantile levels. The findings predominantly show that gold prices are the primary recipients of connectedness in their exchanges with the US dollar for most quantile pairings. However, exceptions arise at particular quantiles, specifically within the ranges of ([τ1 = 10 %, τ2 = 10 90 %], [τ1 = 1075 %, τ2 = 80 ~ 95 %], and [τ1 = 90 %, τ2 = 80 ~ 95 %]). Within these intervals, the role of gold prices shifts to being a net source of connectedness, indicating a movement of connectedness back to the US dollar. This detailed exploration underlines the fluid interaction between gold prices and the US dollar, pointing out that the strength and direction of this relationship significantly fluctuate across various quantile pairs.

The relationship between the US yield curve spread, the US dollar, and gold prices exhibits nuanced dynamics across various quantile levels, underscoring the complexity of their interconnectedness. Specifically, the US yield curve spread generally acts as a net receiver of influence across the spectrum. However, it shifts to a net transmitter role under certain conditions, notably in the quantile pairs ([τ1 = 10 %, τ2 = below 30 %], [τ1 = 10 ~ 95 %, τ2 = 10 %], [τ1 = 10 ~ 95 %, τ2 = 95 %], [τ1 = 70 ~ 95 %, τ2 = 5 ~ 25 %], and [τ1 = 80 ~ 95 %, τ2 = 5 ~ 30 %]). This demonstrates that its relationship with the US dollar can significantly vary depending on the specific quantile pairings, reflecting a more intricate interaction than initially apparent.

Similarly, when analyzing the dynamics between the US yield curve spread and gold price, the typical pattern positions the US yield curve spread as predominantly receiving influence. However, in specific quantile pairings ([τ1 = 7595 %, τ2 = 10 25 %], [τ1 = 10 %, τ2 = 1075 %], [τ1 = 60 ~ 95 %, τ2 = 25 ~ 75 %], and [τ1 = 80 ~ 95 %, τ2 = 1090 %]), the US yield curve spread emerges as the primary source of directional influence, acting as net transmitters. This varied dynamic indicates that the connection between the gold price and the US yield curve spread is not fixed but instead fluctuates significantly across different scenarios.

[1] The analysis was conducted with the R package "Connectedness Approach'' of Gabauer (2022). This R code is also available upon request. See Gabauer and Stenfors (2024) for details about this Quantile-on-Quantile connectedness approach.

Table 3
Unit Root Tests.

	ADF	PP	KPSS	ADF	PP	KPSS
		Level			*First Difference*	
gold	3.061**	−2.959**	0.753***	−3.163*	−30.901***	0.1038
rej	−0.174	−0.130	−0.174	−30.814***	−30.899***	0.1777
X102Y	0.193	−2.185	2.203***	−15.593***	−101.322***	0.315

*, **, and *** are significant at the levels of 10%, 5%, and 1%, respectively.

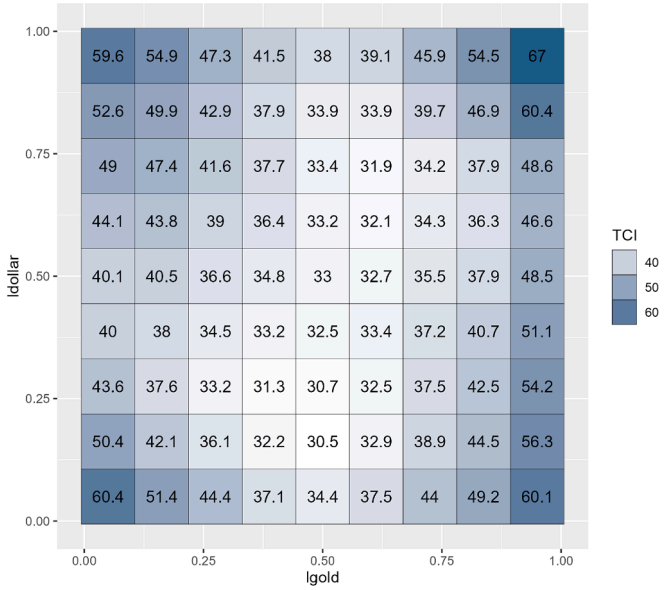

Fig. 5. Average Dynamic Quantile_on_Quantile Total Connectedness for Gold Price and the Dollar where Yield Curve Spread Serves as a Control Variable.

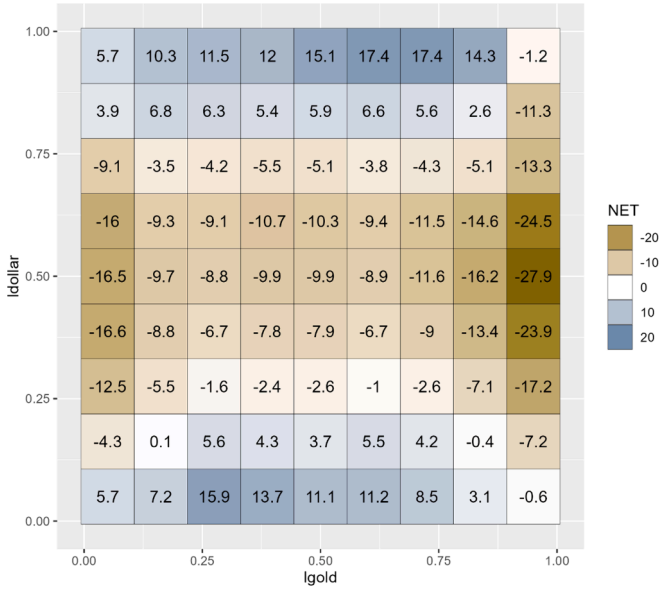

Fig. 6. Net Quantile_on_Quantile Total Connectedness for Gold Price and the Dollar where Yield Curve Spread Serves as a Control Variable.

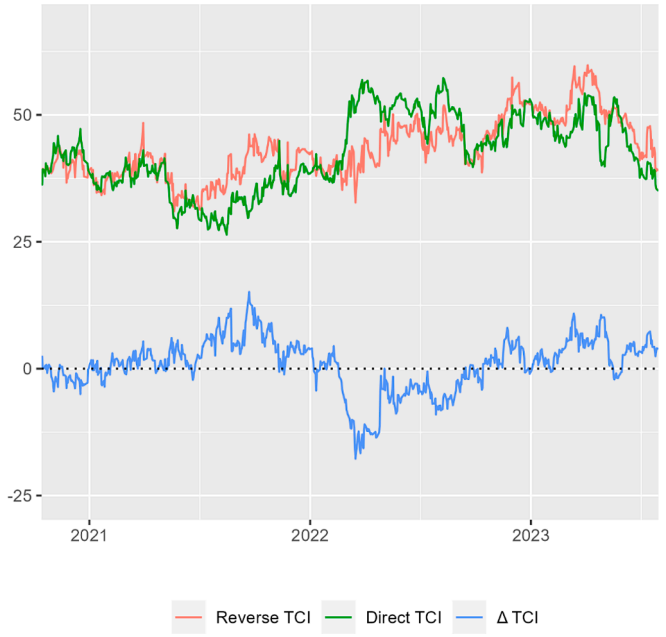

Fig. 7. Dynamic Directly-Related and Reversely-Related Quantiles Total Connectedness for Gold Price and the Dollar where Yield Curve Spread Serves as a Control Variable.

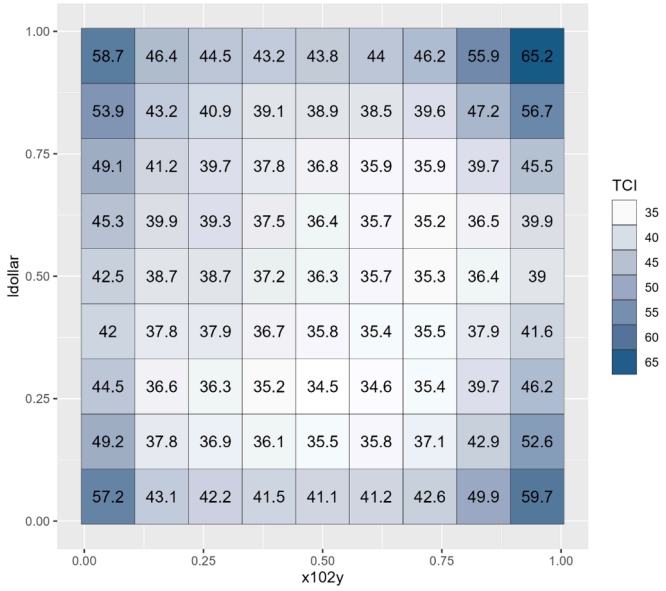

Fig. 8. Average Dynamic Quantile_on_Quantile Total Connectedness, the USA Yield Curve Spread and the Dollar where the Gold Serves as a Control Variable).

This study delves into the intricate and fluctuating relationships among the US dollar, gold price, and the US yield curve spread, uncovering the dynamic nature of their interconnections under various conditions. By analyzing direct and inverse total connectedness across selected quantiles and incorporating control variables (Figs. 7, 10, and 13), the research sheds light on the nuanced interactions between the gold price and the US dollar, the US yield curve spread, and the US dollar, and between the US yield curve spread and gold price. A key finding is the significantly higher level of total connectedness in inverse quantile relationships compared to direct ones, indicating a more complex interdependence when financial indicators move in opposite directions.

The study observes a notable fluctuation in the quantile-based total connectedness over time, peaking in October 2021, especially during the COVID-19 pandemic from January 2000 to July 2023. This highlights the evolving dynamics of financial markets and the

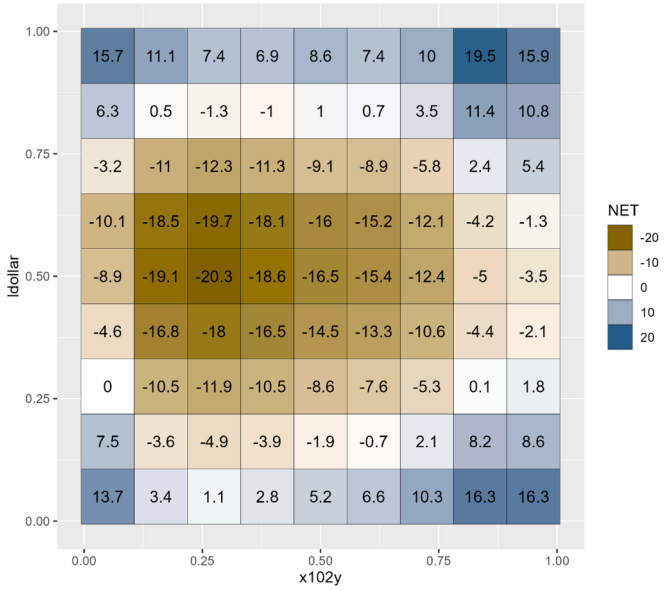

Fig. 9. Net Quantile_on_Quantile Total Connectedness, the Yield Curve Spread and the Dollar where the Gold Price Serves as a Control Variable.

Fig. 10. Dynamic Directly-Related and Reversely-Related Quantiles Total Connectedness, Yield Curve Spread and the Dollar where Gold Serves as a Control Variable.

impact of global events on the interconnectedness of key economic indicators.

Significant relationships were identified using a Quantile-on-Quantile Connectedness approach, particularly between the upper 95 % quantiles of gold prices and the US dollar, the US yield curve spread and the US dollar, and between the US yield curve spread and gold prices. This analysis reveals that inverse correlation quantiles exhibit higher overall connectivity than direct correlations, emphasizing the complex dependency when financial variables move in opposite directions in their distribution tails.

The study further notes the importance of continuous monitoring and adaptation, highlighting the dynamic and robust relationships among these financial indicators. The strongest associations found in the upper 95th percentiles of the analyzed variables underscore the critical nature of these correlations, especially in extreme market conditions.

Figs. 5, 8, and 11 showcase the average dynamic total connectedness indices for three significant financial relationships: between

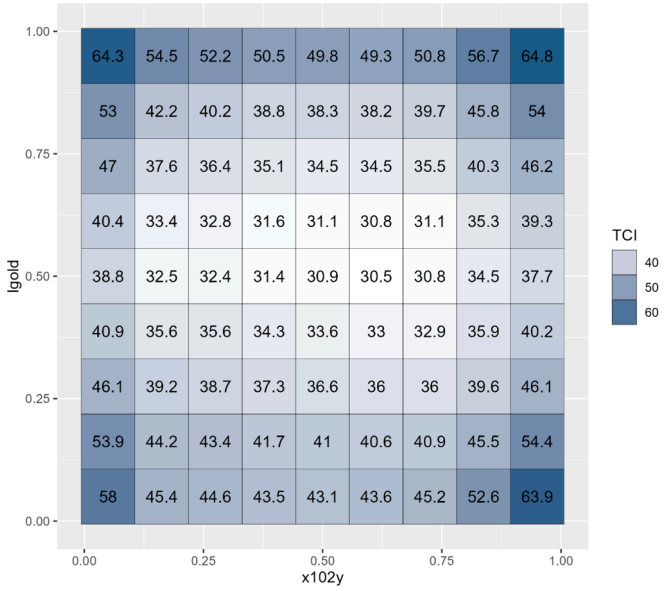

Fig. 11. Average Dynamic Quantile_on_Quantile Total Connectedness, Yield Curve Spread and Gold Prices where the Dollar Serves as a Control Variable.

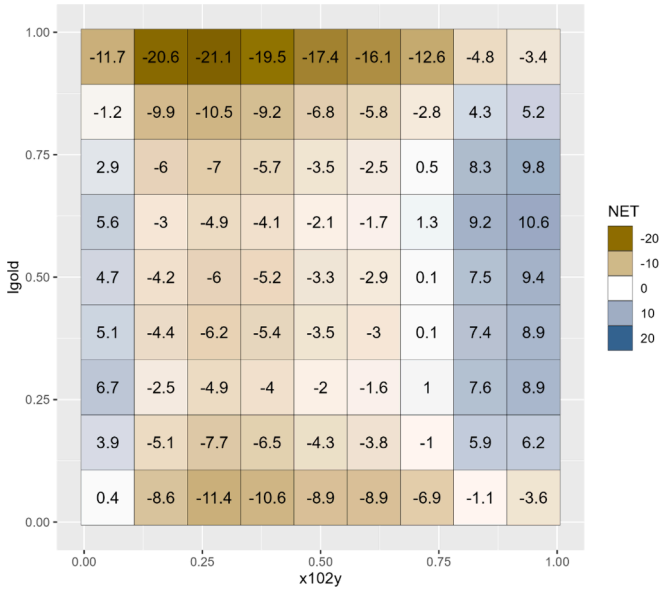

Fig. 12. Net Quantile_on_Quantile Total Connectedness, the Yield Curve Spread and Gold Prices where the Dollar Serves as a Control Variable.

gold prices and the US dollar, the US yield curve spread and the US dollar, and the US yield curve spread and gold price, across the bivariate quantile spectrum. These analyses illuminate a consistent pattern in connectedness based on the directionality of quantile pairs.

For gold price and the US dollar relationship, inversely related quantiles, ranging from [$\tau1 = 10\,\%, \tau2 = 95\,\%$] to [$\tau1 = 90\,\%, \tau2 = 25\,\%$], are found to have weaker connectedness than directly related quantiles ([$\tau1 = 10\,\%, \tau2 = 10\,\%$] to [$\tau1 = 95\,\%, \tau2 = 95\,\%$]). However, exceptions for the pairs ([$\tau1 = 10\,\%, \tau2 = 10\,\%$], [$\tau1 = 75\,\%, \tau2 = 90\,\%$] and [$\tau1 = 95\,\%, \tau2 = 95\,\%$]) indicate that directly related quantiles can also exhibit more pronounced connectedness in certain instances.

A similar pattern emerges in the interaction between the US yield curve spread and the US dollar, where inversely related quantiles ([$\tau1 = 5\,\%, \tau2 = 95\,\%$] [$\tau1 = 20\,\%, \tau2 = 90\,\%$] [$\tau1 = 30\,\%, \tau2 = 80\,\%$], and [$\tau1 = 45\,\%, \tau2 = 60\,\%$]) show stronger connectedness than directly related ones ([$\tau1 = 5\,\%, \tau2 = 5\,\%$] to [$\tau1 = 95\,\%, \tau2 = 95\,\%$]). This mirrored pattern in both financial relationships suggests a consistent trend in the dynamics of these variables across various quantile pairs, highlighting the nuanced and varied nature of their

Fig. 13. Dynamic Directly-Related and Reversely-Related Quantiles Total Connectedness for Yield Curve Spread and the Gold Prices where the Dollar Serves as a Control Variable.

interconnectedness.

The analysis of the interaction between the US yield curve spread and gold price reveals a notable trend: inversely related quantile pairs ([τ1 = 5 %, τ2 = 95 %], [τ1 = 60 %, τ2 = 45 %], and [τ1 = 75 %, τ2 = 30 %]), and repeating for emphasis, demonstrate more substantial connectedness compared to directly related quantile pairs ([τ1 = 5 %, τ2 = 5 %] through to [τ1 = 95 %, τ2 = 95 %]). However, deviations from this pattern are observed in the quantile pairs ([τ1 = 80 %, τ2 = 80 %] and [τ1 = 95 %, τ2 = 95 %]), where directly related quantiles show stronger connectedness than their inversely related counterparts.

This pattern suggests a general trend where inversely related quantiles exhibit stronger connections across the examined financial relationships. Nonetheless, specific exceptions highlight these interactions' complexity and nuanced nature, indicating that the relationship between the US yield curve spread and gold price is not uniformly predictable but varies significantly under different conditions.

Figs. 6, 9, and 12 delve into the Quantile-on-Quantile total directional connectedness, shedding light on the complex dynamics between the US dollar, gold prices, and the US yield curve spread across diverse quantile levels. The findings predominantly show that gold prices act as the primary recipients of connectedness in their exchanges with the US dollar for most quantile pairings. However, exceptions arise at particular quantiles, specifically within the ranges of ([τ1 = 10 %, τ2 = 10 ~ 90 %], [τ1 = 10 ~ 75 %, τ2 = 80 ~ 95 %], and [τ1 = 90 %, τ2 = 80 ~ 95 %]). Within these intervals, the role of gold prices shifts to being a net source of connectedness, indicating a movement of connectedness back to the US dollar. This detailed exploration underlines the fluid nature of the interaction between gold prices and the US dollar, pointing out that the strength and direction of this relationship significantly fluctuate across various quantile pairs.

The relationship between the US yield curve spread, the US dollar, and gold prices exhibits nuanced dynamics across various quantile levels, underscoring the complexity of their interconnectedness. Specifically, the US yield curve spread generally acts as a net receiver of influence across the spectrum. However, it shifts to a net transmitter role under certain conditions, notably in the quantile pairs ([τ1 = 10 %, τ2 = below 30 %], [τ1 = 10 ~ 95 %, τ2 = 10 %], [τ1 = 10 ~ 95 %, τ2 = 95 %], [τ1 = 70 ~ 95 %, τ2 = 5 ~ 25 %], and [τ1 = 80 ~ 95 %, τ2 = 5 ~ 30 %]). This demonstrates that its relationship with the US dollar can significantly vary depending on the specific quantile pairings, reflecting a more intricate interaction than initially apparent.

Similarly, when analyzing the dynamics between the US yield curve spread and gold price, the typical pattern positions the US yield curve spread as predominantly receiving influence. However, in specific quantile pairings ([τ1 = 75 ~ 95 %, τ2 = 10 ~ 25 %], [τ1 = 10 %, τ2 = 10 ~ 75 %], [τ1 = 60 ~ 95 %, τ2 = 25 ~ 75 %], and [τ1 = 80 ~ 95 %, τ2 = 10 ~ 90 %]), the US yield curve spread emerge as the primary source of directional influence, acting as net transmitters. This varied dynamic indicates that the connection between the gold price and the US yield curve spread is not fixed but fluctuates significantly across different scenarios.

This study delves into the intricate and fluctuating relationships among the US dollar, gold price, and the US yield curve spread, uncovering the dynamic nature of their interconnections under various conditions. By analyzing direct and inverse total connectedness across selected quantiles and incorporating control variables (Figs. 7, 10, and 13), the research sheds light on the nuanced interactions between the gold price and the US dollar, the US yield curve spread, and the US dollar, and between the US yield curve spread and gold price. A key finding is the significantly higher level of total connectedness in inverse quantile relationships compared to direct ones,

indicating a more complex interdependence when financial indicators move in opposite directions.

The study observes a notable fluctuation in the quantile-based total connectedness over time, peaking in October 2021, especially during the COVID-19 pandemic from January 2000 to July 2023. This highlights the evolving dynamics of financial markets and the impact of global events on the interconnectedness of key economic indicators.

Significant relationships were identified using a Quantile-on-Quantile Connectedness approach, particularly between the upper 95 % quantiles of gold prices and the US dollar, the US yield curve spread and the US dollar, and between the US yield curve spread and gold prices. This analysis reveals that inverse correlation quantiles exhibit higher overall connectivity than direct correlations, emphasizing the complex dependency when financial variables move in opposite directions in their distribution tails.

The study further notes the importance of continuous monitoring and adaptation, highlighting the dynamic and robust relationships among these financial indicators. The strongest associations found in the upper 95th percentiles of the analyzed variables underscore the critical nature of these correlations, especially in extreme market conditions.

Directional connectivity analysis showcases the variable roles of these financial indicators as net senders or receivers of impacts across different quantile combinations, suggesting a nuanced and evolving pattern of interactions. This has significant implications for economic policy-making, risk management, and investment strategies, particularly during heightened market uncertainty.

The research emphasizes the critical need to understand the complex interdependencies between financial variables, such as the US dollar, gold prices, and the US yield curve spread. By employing a Quantile-on-Quantile approach, the study uncovers subtle, time-varying interconnections that are pivotal for managing risks and formulating strategies in dynamic market conditions.

4 **Policy implications of our empirical findings**

The investigation into the Quantile-on-Quantile transmission dynamics among the US yield curve spread, gold price, and the US dollar during the COVID-19 pandemic reveals pivotal findings with significant implications for policy formulation.

The significant findings of more vital connectedness in inversely related quantiles underscore the importance of recognizing and understanding complex dependencies between financial variables. Policymakers and financial analysts must know that the relationships between critical indicators like the US dollar, gold prices, and the US yield curve spread are not static and can vary significantly across different market conditions.

The fluctuating nature of these interconnections, particularly during periods of heightened market uncertainty like the COVID-19 pandemic, highlights the need for robust risk management strategies. Financial institutions and investors should continuously monitor these dynamics and adjust their strategies to mitigate risks associated with extreme market movements.

The insights gained from this study can inform investment strategies, particularly in identifying periods of heightened connectedness that may signal increased volatility. Investors can leverage this information to make more informed decisions, potentially adjusting their portfolios to hedge against adverse movements in the US dollar, gold prices, and the yield curve spread.

The dynamic and evolving nature of the interconnectedness between these financial variables implies that economic policies must be adaptable and responsive to changing market conditions. Policymakers should consider these findings when designing interventions to stabilize financial markets and promote economic resilience.

The strong associations in the upper 95th percentiles of the analyzed variables underscore the need for special attention during extreme market conditions. Policymakers and financial analysts should be particularly vigilant in these scenarios, as the interactions between financial indicators can become more pronounced and potentially destabilizing.

This study emphasizes the critical need to understand the complex interdependencies between financial variables such as the US dollar, gold prices, and the US yield curve spread. By employing a Quantile-on-Quantile approach, the research uncovers subtle, time-varying interconnections that are pivotal for managing risks and formulating strategies in dynamic market conditions.

7. Conclusions

In our study spanning from January 2, 2020, to July 31, 2023—a period notably affected by the COVID-19 pandemic—we utilized the Quantile-on-Quantile Connectedness method innovated by Gabauer and Stenfors (2024) to explore the dynamics among the US yield curve spread, gold price, and the US dollar. Our analysis highlighted a key finding: reversely related quantiles demonstrate significantly higher total connectedness than directly related quantiles, with this disparity persisting throughout the study period. Additionally, we observed a marked variability in quantile-based connectedness over time, which appeared to align with specific economic milestones. This underscores the necessity of considering both reversely and directly related quantile dynamics for a fuller understanding.

However, our study acknowledges several limitations. Firstly, despite its novelty, the Quantile-on-Quantile Connectedness framework may be susceptible to model-specific constraints, such as sensitivity to quantile selection or foundational assumptions not entirely encompassing market complexities. Secondly, while unique, the focus on the pandemic era might restrict our findings' broader applicability. Thirdly, identifying causality between variables remains elusive, as the study mainly uncovers correlations and connectedness. Fourthly, we may overlook other vital financial assets and indicators by concentrating solely on the yield curve spread, gold prices, and the dollar. Lastly, the study's temporal scope and data specificity could miss broader market dynamics or external influences, with data quality and depth affecting outcomes.

Future research addressing these limitations could deepen our comprehension of financial market interconnectedness and refine policy guidance.

CRediT authorship contribution statement

Mei-Chih Wang: Software, Data curation. **Tsangyao Chang:** Supervision, Methodology. **Alexey Mikhaylov:** Writing – original draft. **Jia Linyu:** .

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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