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Biodiversity finance, green bonds, and tokenized carbon: a Quantile-on-Quantile connectedness analysis

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ABSTRACT

Biodiversity is critical to ecological and financial stability, yet its integration into sustainable finance remains underexplored. This study analyzes the dynamic connectedness between biodiversity finance, green bonds, and tokenized carbon assets using the Quantile-on-Quantile Connectedness framework developed by Gabauer and Stenfors (2024). Results reveal nonlinear, state-dependent spillovers that intensify under extreme market conditions. Biodiversity assets alternate between shock transmitters and receivers, with implications for ESG portfolio construction and systemic risk oversight. The findings indicate the value of quantile-based modeling and support the case for nature-aligned financial regulation and risk management.

1. Introduction

Biodiversity is a fundamental pillar of ecological and economic stability, critical ecosystem services such as climate regulation, food security, and disaster resilience (Chopra et al., 2024). However, biodiversity loss, accelerated by climate change, deforestation, industrial expansion, and unsustainable land use, has reached alarming levels, with wildlife populations declining by 73 % over the past five decades (Nie and Zhang, 2025). The increasing degradation of biodiversity poses a significant threat to environmental sustainability and systemic risks to financial markets and economic development (Hasan et al., 2025; El Ouadghiri et al., 2025). These risks are drawing increased attention from investors, policymakers, and regulators alike, catalyzing the emergence of biodiversity finance as a vital subdomain of sustainable finance (Jonäll et al., 2025; Flammer et al., 2025).

Biodiversity finance refers to strategies and instruments that mobilize private capital to support biodiversity conservation and ecosystem restoration (Flammer et al., 2025). As indicated by Seidl et al. (2024), aligning financial flows with the goals of the Kunming-Montreal Global Biodiversity Framework requires innovative tools such as biodiversity credits, green bonds, and fiscal transfers. Green bonds have become a key vehicle for funding projects that advance environmental sustainability, including biodiversity-positive investments (Gao et al., 2025). Integrating biodiversity considerations into green bond frameworks represents a promising pathway to align financial and ecological incentives, yet empirical evidence on the strength and structure of this relationship remains sparse.

In parallel, the digitalization of sustainable finance has introduced a new class of blockchain-based environmental assets. Tokenized carbon credits and ESG-focused cryptocurrencies are designed to enhance transparency, traceability, and accessibility in environmental asset markets (El Ouadghiri et al., 2025). These instruments are increasingly complementary to traditional finance, potentially facilitating decentralized ecosystem service markets and offsetting verifiable emissions. However, the integration of tokenized ESG assets into broader biodiversity finance remains conceptually and empirically underexplored. In particular, their

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interconnectedness with traditional biodiversity and green bond markets under varying market conditions has yet to be systematically examined.

From a theoretical standpoint, these three assets (biodiversity-linked equity indices, green bonds, and tokenized carbon credits) are interconnected through their shared alignment with nature-based financial objectives. Studies by Portillo-Quintero et al. (2015) and Jung et al. (2021) provide strong evidence that ecosystems rich in biodiversity, such as tropical forests, often also serve as major carbon sinks, establishing a mutual reinforcement between biodiversity conservation and carbon storage. The implication is that biodiversity assets and carbon-offset mechanisms are not parallel efforts but overlapping instruments in achieving sustainability goals. Di Marco et al. (2018) further note that while the carbon–biodiversity relationship is spatially heterogeneous, areas where similar environmental conditions drive both exhibit co-benefits, justifying their joint inclusion in ecological finance models. Moreover, green finance channels such as labeled green bonds serve as critical enablers of capital mobilization for nature-related goals (Gao et al., 2025), while digital assets like the MCO2 token, backed by verified forest carbon offsets, represent the convergence of technological innovation and ecological finance (Barclay et al., 2022). This triangulated framework aligns with Seidl et al. (2024), who emphasize the need for blended public-private instruments to fund the biodiversity agenda. In essence, the three markets under study reflect different modalities of pricing ecosystem services: equity-based exposure (biodiversity indices), debt-based financing (green bonds), and digital commodity valuation (carbon tokens). This conceptual complementarity provides a strong basis for hypothesizing financial interconnectedness, especially under sustainability-driven market shifts.

Despite this conceptual interdependence, current empirical research essentially treats these domains in isolation. Most studies have examined green finance in relation to clean energy (Ozkan et al., 2024; Shah et al., 2024; Lang et al., 2024), while the integration of biodiversity-linked instruments with carbon and fixed-income markets remains fragmented (Jonäll et al., 2025). To our knowledge, no prior research has jointly modeled the connectedness of biodiversity finance, green bonds, and tokenized carbon credits within a single empirical framework. This omission is significant given the growing momentum to harmonize nature-related financial disclosures, metrics, and capital flows. Moreover, given the potential for non-linear dependencies and asymmetric shock transmission, it is imperative to examine how these markets interact under varying financial conditions, including stress episodes and bullish phases (Tian and Chen, 2025; Liang et al., 2024).

This study addresses these gaps by investigating the dynamic connectedness among biodiversity finance, green bond markets, and tokenized carbon assets using a Quantile-on-Quantile Connectedness (QQC) approach developed by Gabauer and Stenfors (2024). While the traditional Quantile Connectedness approach estimates spillovers at corresponding quantiles (e.g., 5th to 5th, 50th to 50th), QQC allows a detailed cross-quantile analysis, examining how the return of one asset at a specific quantile (e.g., extreme loss) affects another asset at all quantile levels. This is particularly powerful in sustainable finance, where asymmetric spillovers and state-contingent dynamics, such as sudden biodiversity policy shocks or swings in the carbon credit market, may propagate differently under bullish or bearish regimes. Furthermore, a key methodological innovation in our application is the decomposition of the Total Connectedness Index (TCI) into direct TCI, reverse TCI, and their differential (ΔTCI), which provides novel insights into the dominant direction of influence over time. We also compute net pairwise spillovers across quantile combinations, enabling a detailed mapping of who transmits and who absorbs shocks under varying market conditions.

This study's central research question is: "How do biodiversity finance indices, green bond markets, and blockchain-based ESG assets interact dynamically across different market conditions, and what implications do these relationships have for investors and policymakers?". This paper contributes to the sustainable finance literature in several key ways. First, it provides novel empirical insights into the nonlinear and asymmetric interdependencies between biodiversity-linked, green fixed income, and digital ESG assets. Second, it introduces blockchain-based environmental assets as a credible and relevant component of biodiversity finance, expanding the field's traditional boundaries. Third, it applies the QQC methodology to discover cross-quantile spillovers and tail-risk transmission dynamics often overlooked in mean-based models.

The remainder of the paper is structured as follows. Section 2 describes the data and outlines the methodological framework. Section 3 presents the empirical findings and discusses their implications. Section 4 concludes with a summary of key insights and recommendations for financial practitioners and policymakers.

2. Data description and research methodology

2.1. Data description

We employ three distinct financial instruments that represent the central pillars of the sustainable investment ecosystem: the S&P 500 Biodiversity Index, the S&P Green Bond Index, and the Moss Carbon Credit Token (MCO2). These instruments capture key dimensions of the sustainable finance landscape, including biodiversity-aware equity portfolios, fixed-income vehicles for green investment, and digital assets that tokenize environmental impact. The S&P 500 Biodiversity Index, developed by S&P Global, comprises firms in the S&P 500 that demonstrate measurable commitments to reducing biodiversity-related risks through operational practices and corporate disclosures. To enhance the robustness and generalizability of our results, we also incorporate the S&P Global Large-MidCap Biodiversity Index as an alternative proxy for biodiversity. This global index extends beyond the U.S. market to include large- and mid-cap firms across both developed and emerging economies, selected based on S&P Global Sustainable1's ESG and biodiversity screening methodologies. It enables us to test whether the observed spillover patterns persist when biodiversity exposure is expanded geographically and sectorally.

To reflect the growing role of digital innovation in ESG markets, we incorporate MCO2. This blockchain-based token is backed by verified voluntary carbon credits tied to forest conservation and reforestation initiatives, primarily in the Amazon region. MCO2 introduces decentralized, verifiable mechanisms into carbon finance, providing a novel perspective on how tokenized environmental assets integrate into the broader sustainable finance ecosystem. The data covers the period from March 17, 2021, to May 30, 2025. This start date is determined by the availability of historical price data for the MCO2 token, which became accessible from mid-March 2021 onward. This timeframe enables us to capture diverse market regimes, including post-pandemic recovery dynamics, major biodiversity-related policy events (e.g., COP15), and shifts in ESG investment sentiment. Daily closing price data for the S&P 500 Biodiversity Index, green bond index, and the S&P Global Large-MidCap Biodiversity Index were obtained from S&P Global. Historical price data for the MCO2 token were sourced from CoinCodex.com. All price series were transformed into daily logarithmic returns and synchronized to a standard trading calendar. Table 1 illustrates the descriptive statistics of the data.

The mean returns are close to zero for all indices, except for the MCC, which exhibits a slight negative drift. MCC also exhibits the highest variance, indicating elevated volatility relative to the other ESG assets. Skewness and kurtosis values suggest significant deviations from normality, particularly for MCC, which is highly right-skewed and leptokurtic. All series reject the null hypothesis of normality based on the Jarque–Bera test at the 1 % level. The ADF, PP, and ERS tests across all assets confirm the stationarity of the data. Moreover, Q(20) and $Q^2(20)$ statistics highlight the presence of serial correlation and conditional heteroskedasticity, especially in MCC and GLB, justifying the use of quantile-based and volatility-sensitive modeling frameworks.

2.2. Research methodology

This study applies the QQC framework, which extends the quantile connectedness model of Chatziantoniou et al. (2021) by allowing the analysis of interconnectedness across different quantiles of the return distributions. We follow the approach developed by Gabauer and Stenfors (2024), which incorporates quantile vector autoregressions (QVAR) to estimate dynamic dependencies between variables across a broad range of distributional conditions, rather than at a single central tendency. The QQ framework begins with the estimation of a QVAR(p) model, as shown in Eq. (1):

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

where x_t is an $N \times 1$ of endogeneous variables, $\mu(\tau)$ is a vector of quantile-dependent intercepts, $B_j(\tau)$ denotes $N \times N$ matrix of quantile-specific autoregressive coefficients for lag j, and $u_t(\tau) isavectoroferrortermsatquantile \tau$ with associated variance-covariance matrix $\sum(\tau)$. To analyze connectedness, the QVAR model is expressed in its infinite-order moving average form via the Wold decomposition:

$$x_t = \mu(\tau) + \sum_{j=1}^{p} B_j(\tau)x_{t-j} + u_t(\tau) = \mu(\tau) + \sum_{i=0}^{\infty} A_i(\tau)u_{t-1}(\tau) \tag{2}$$

This representation enables the computation of generalized forecast error variance decompositions (GFEVD), which measure how shocks to one variable at a given quantile influence the forecast error variance of another. The F-step ahead GFEVD is calculated as follows:

$$\varnothing^{g}_{i\leftarrow j,\tau}(F) = \frac{\sum_{f=0}^{F-1}\left(e_i' A_f(\tau)H(\tau)e_j\right)^2}{H_{ii}(\tau)\sum_{f=0}^{F-1}\left(e_i' A_f(\tau)H(\tau)A_f(\tau)' e_i\right)} \tag{3}$$

$$gSOT_{i\leftarrow j,\tau}(F) = \frac{\varnothing^{g}_{i\leftarrow j,\tau}(F)}{\sum_{j=1}^{k}\varnothing^{g}_{i\leftarrow j,\tau}(F)} \tag{4}$$

Table 1
Descriptive statistics of the data.

	SPB	SGB	MCC	GLB
Mean	0.0004	-0.0001	-0.0045	0.0003
Variance	0.0001	0.000023	0.0067	0.0001
Skewness	0.026	0.224***	4.360***	-0.220***
Kurtosis	5.898***	1.850***	53.580***	3.662***
JB	1502.968***	156.465***	127,328.400***	587.682***
ADF	-9.5116***	-8.5634***	-8.8373***	-9.3822***
PP	-983.1034***	-918.6929***	-1109.9194***	-787.0280***
ERS	-14.723***	-9.880***	-7.040***	-14.492***
Q(20)	28.226	33.542**	80.180***	54.627***
Q^2(20)	183.199***	94.492***	17.099*	199.050***

Note: SPB denotes the S&P 500 Biodiversity Index, SGB refers to the S&P Green Bond Index, MCC represents the Moss Carbon Credit Token, and GLB stands for the S&P Global Large-MidCap Biodiversity Index. JB is the Jarque–Bera test for normality, ADF and PP denote Augmented Dickey–Fuller and Phillips–Perron unit root tests, respectively, while ERS indicates the Elliot–Rothenberg–Stock test. Q(20) and $Q^2(20)$ are the Ljung–Box statistics for the autocorrelation of returns and squared returns up to lag 20. ***, **, and * denote statistical significance at the 1 %, 5 %, and 10 % levels, respectively.

where e_i is a selection vector with 1 in the i^{th} position and zero elsewhere. The scaled GFEVD $gSOT_{i \leftarrow j,\tau}(F)$ ensures the decompositions sum to one, facilitating interpretation across variables and quantiles. The directional connectedness from variable i to others is computed as:

$$S^{gen,to}_{i\rightarrow\cdot,\tau} = \sum_{k=1,i\neq j}^{k} gSOT_{k\leftarrow i,\tau} \tag{5}$$

Conversely, the directional connectedness from others to variable i is given by:

$$S^{gen,from}_{i\leftarrow\cdot,\tau} = \sum_{k=1,i\neq j}^{k} gSOT_{i\leftarrow k,\tau} \tag{6}$$

Finally, the TCI provides a summary of spillovers across all series:

$$TCI_\tau(F) = \frac{k}{k-1}\sum_{k=1}^{k} S^{gen,from}_{i\leftarrow\cdot,\tau} \equiv \frac{k}{k-1}\sum_{k=1}^{k} S^{gen,to}_{i\rightarrow\cdot,\tau} \tag{7}$$

This adjusted TCI captures the extent of systemic interdependence, varying by quantile and reflecting how linkages change under different market conditions, including those associated with tail events, which are particularly relevant for ESG-related assets.

3. Empirical results

This section illustrates the average connectedness metrics between Biodiversity and Green bonds/Digital ESG Assets and interprets the dynamic direct and inverse quantile total connectedness.

3.1. Quantile-on-Quantile connectedness between biodiversity and green bonds

Fig. 1 displays the Quantile-on-Quantile TCI between the S&P 500 Biodiversity Index and the S&P Green Bond Index across various quantile pairings. The horizontal and vertical axes represent the quantiles of the S&P Green Bond and S&P Biodiversity returns, ranging from 0.1 (bearish market) to 0.9 (bullish market) quantiles.

The quantile-on-quantile heatmap of TCI indicates that the relationship between biodiversity finance and green bond markets is highly state-dependent. Connectedness is most pronounced at the upper ends of the return distributions, particularly when both

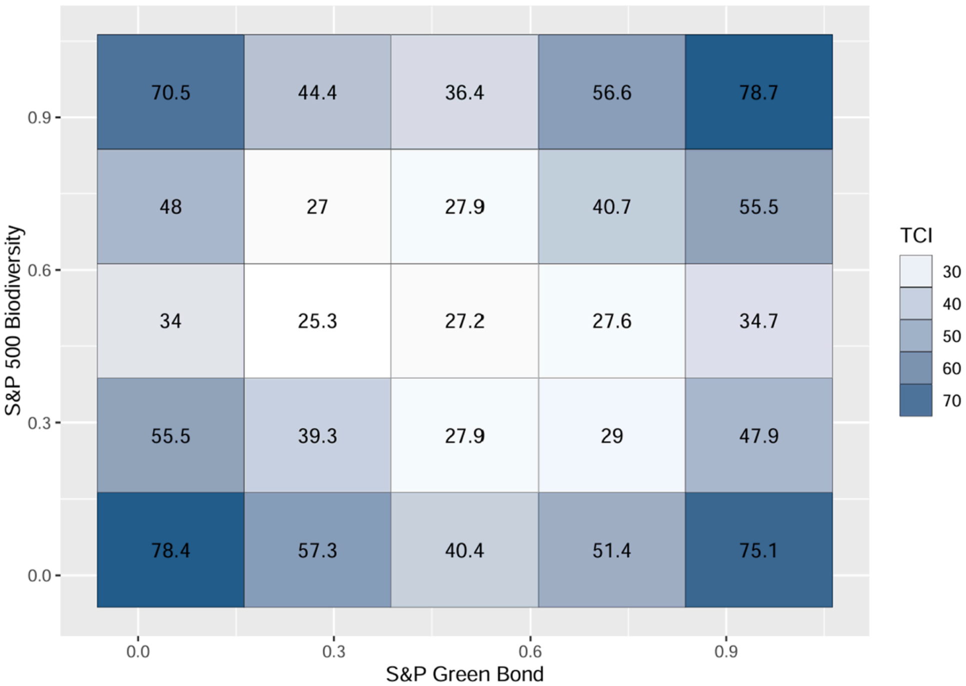

Fig. 1. Quantile-on-Quantile total connectedness index between S&P 500 biodiversity index and S&P green bond index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

biodiversity and green bond returns lie in the top quantiles. The TCI peaks at 78.7 when $\tau = 0.9$ and $k = 0.9$, indicating that strong positive performance in both markets significantly amplifies interconnectedness. This suggests that during periods of sustainability-driven optimism or coordinated ESG fund inflows, spillover effects become more synchronized across asset classes. Similarly high TCI values (78.4) are also observed in the lower tail, indicating that extreme downside shocks intensify cross-market dependencies as well. These findings reflect a U-shaped pattern, where connectedness is stronger in both boom-and-bust conditions, possibly due to herd-like behavior, joint valuation adjustments, or correlated policy responses in sustainability-focused assets. In contrast, mid-quantile regions (e.g., $\tau = 0.3$–0.6, $k = 0.3$–0.6) exhibit notably lower levels of spillovers, with TCI values dropping to the 25–30 range. This indicates that under neutral or average market conditions, biodiversity and green bond markets are relatively decoupled, offering potential diversification benefits for multi-asset ESG portfolios. The asymmetric and nonlinear spillover structure highlights the importance of employing quantile-based approaches, such as the QQC framework, to fully capture state-dependent dynamics in ESG-linked assets.

These results are consistent with the idea that biodiversity and green bond markets become more interconnected during extreme market regimes, a feature also observed in other ESG-linked asset classes. For example, Saeed et al. (2021) highlight that tail risk spillovers between clean and dirty energy markets are stronger at both extremes of the return distribution, emphasizing nonlinear contagion during crises or booms. Similarly, our U-shaped connectedness pattern aligns with their finding of asymmetrical tail risk dynamics, reinforcing the need for quantile-based approaches. Moreover, the amplified spillovers under bullish ESG conditions reflect coordinated investor sentiment and flows, a behavior also reported in green bond–clean energy linkages (Ozkan et al., 2024).

Fig. 2 presents the quantile-on-quantile net connectedness heatmap, indicating the directional dominance of spillovers between biodiversity finance and green bond markets. Positive values indicate that the biodiversity index acts as a net transmitter of shocks, while negative values reflect its role as a net absorber of shocks.

Fig. 2 indicates a pronounced asymmetry in net directional connectedness between the S&P 500 Biodiversity Index and the S&P Green Bond Index, contingent on their joint return states. The most significant positive net spillovers occur when biodiversity returns are in the lowest quantile (τ= 0.1) and green bond returns range from neutral to high (e.g., $k = 0.3$ to 0.6). The highest net transmission is observed at (τ= 0.1, $k = 0.6$) with a value of 25.1, indicating that severe adverse shocks in biodiversity markets are a dominant source of volatility for green bonds, likely reflecting synchronized ESG de-risking or climate-related sentiment contagion. Conversely, when biodiversity returns are in the mid-quantile range (τ= 0.3 to 0.6), the net connectedness values are predominantly negative, with the strongest absorption at (τ= 0.5, $k = 0.1$) and (τ= 0.5, $k = 0.9$), where net values drop to –17.5 and –14.4, respectively. These patterns suggest that during more stable or moderately rising biodiversity markets, green bond returns exert a more decisive influence, possibly due to macroeconomic shifts in fixed-income pricing, green fiscal interventions, or forward-looking carbon policy announcements.

At the upper tail of biodiversity returns (τ= 0.9), the net connectedness becomes modestly positive, particularly at (τ= 0.9, $k = 0.6$)

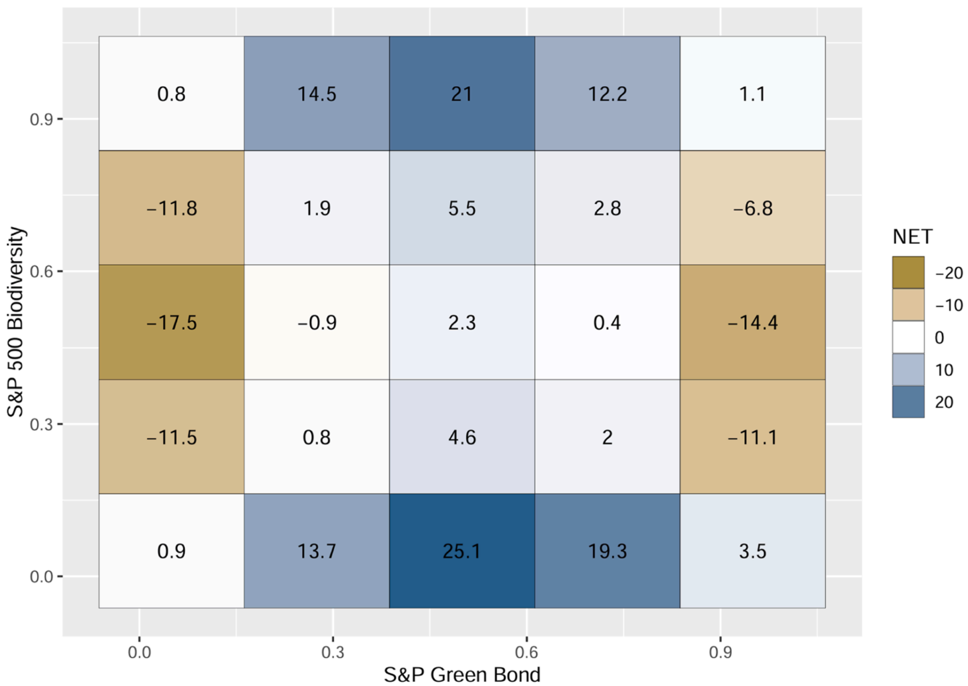

Fig. 2. Net Quantile-on-Quantile connectedness between S&P 500 biodiversity index and S&P green bond index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

and ($\tau = 0.9$, $k = 0.3$) with values of 21 and 14.5, respectively. This indicates a return of transmitting power during bullish biodiversity phases, especially when green bond returns are in neutral zones. Meanwhile, when green bond returns are extremely high ($k = 0.9$), biodiversity's net role becomes neutral or slightly positive. These findings confirm the state-dependent and bidirectional nature of ESG spillovers. The biodiversity index acts as a net transmitter in extreme conditions, both downturns and rallies, while transitioning to a net receiver role under intermediate or calm conditions.

The asymmetric directional patterns in our results align with recent studies that have shown time-varying leadership roles among ESG assets. For instance, Lang et al. (2024) observe alternating transmission roles between clean and dirty energy under different macro conditions, driven by policy uncertainty and market sentiment. Similarly, we find that biodiversity finance acts as a net transmitter during crisis and optimism phases, and as a receiver during policy-sensitive transitions, mirroring the dynamic dominance documented in other sustainable asset networks.

Fig. 3 illustrates the temporal evolution of the average direct and reverse TCI across quantiles, alongside the net connectedness (Δ TCI) between the S&P 500 Biodiversity Index and the S&P Green Bond Index. The green and red lines represent the average connectedness transmitted from biodiversity to green bonds (direct TCI) and vice versa (reverse TCI). The blue line (Δ TCI) captures the net direction of spillovers over time.

Fig. 3 illustrates that interconnectedness is persistently strong and fluctuates across the sample period, with both direct and reverse TCI values remaining elevated, often within the 35–65 range. The net connectedness (ΔTCI), shown by the blue line, oscillates notably around the zero line, reflecting dynamic shifts in volatility leadership between the two markets. From late 2021 through early 2022, ΔTCI is consistently positive, suggesting that biodiversity finance acted as a net transmitter of shocks to the green bond market. This period coincides with key developments such as the first part of COP15 (October 2021) and early momentum around the Taskforce on Nature-related Financial Disclosures (TNFD), which likely amplified investor focus on biodiversity-related risks and systemic signals. During the mid-2022 to early 2023 period, the ΔTCI became predominantly negative, indicating that green bond markets took over as the primary source of volatility. This regime shift aligns with the global interest rate tightening cycle, during which green bonds, being fixed-income instruments, became more sensitive to monetary policy shocks. Consequently, biodiversity assets behaved more defensively, absorbing rather than transmitting volatility across the ESG asset space.

From late 2024 to early 2025, the ΔTCI line exhibits renewed and more pronounced positive surges, indicating that biodiversity assets are regaining systemic influence and becoming key transmitters of volatility once again. This could be linked to sharp biodiversity policy disclosures, nature-related investment innovation, or rising investor sensitivity to ecological transitions embedded in climate finance narratives.

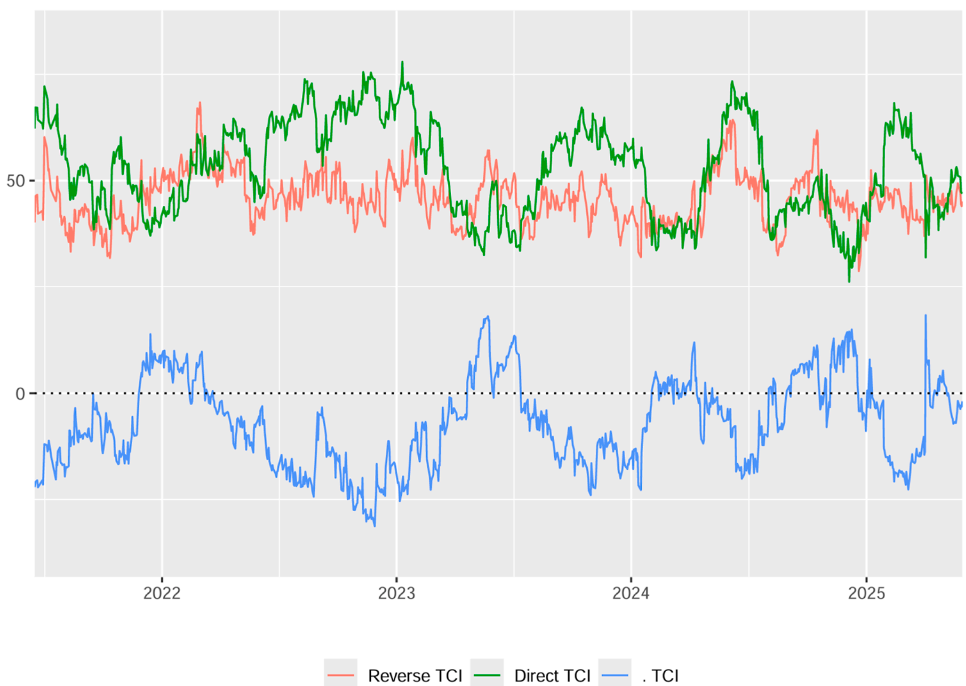

Fig. 3. Time-Varying Direct, Reverse, and Net Total Connectedness (ΔTCI) between S&P 500 Biodiversity Index and S&P green bond index. Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

3.2. Quantile-on-Quantile connectedness between biodiversity and digital ESG assets

Fig. 4 presents the Quantile-on-Quantile TCI between the S&P 500 Biodiversity Index and the MCO2. The heatmap demonstrates how spillovers vary across different quantile pairings of biodiversity and tokenized carbon returns, indicating nonlinear and state-dependent connectedness.

Fig. 4 illustrates clear nonlinear patterns in total connectedness across the return quantiles of the S&P 500 Biodiversity Index and MCO2. The highest spillover intensities, TCI values above 70, are concentrated in the extreme quantile corners, particularly at ($\tau= 0.1$, $k = 0.1$) with a TCI of 70.4 and at ($\tau= 0.9$, $k = 0.9$) with a TCI of 74.1. This confirms that tail co-movements, where both markets experience simultaneous surges or downturns, are associated with the strongest interconnectedness, likely reflecting systemic environmental or crypto-finance shocks. In contrast, the center of the distribution, particularly combinations such as ($\tau= 0.5$, $k = 0.5$) and ($\tau= 0.6$, $k = 0.6$), exhibits weaker spillovers, with TCI values ranging from 22.9 to 24.3. These lower values suggest that during neutral or average return states, the relationship between biodiversity finance and tokenized carbon becomes weaker, allowing for potential diversification benefits during stable periods.

An asymmetric pattern is also visible: when biodiversity returns lie in the lower quantiles, connectedness tends to be higher across all MCO2 states (e.g., TCI= 70.4 at $\tau= 0.1$, $k = 0.1$ and TCI= 55.6 at $\tau= 0.3$, $k = 0.9$), indicating that adverse biodiversity shocks tend to transmit more systemic risk than positive ones. These results demonstrate the importance of tail-dependent modeling for ESG portfolios that include both natural capital equities and blockchain-based environmental assets, particularly for capturing contagion effects during joint stress episodes. Our finding of strong tail co-movements between biodiversity and tokenized carbon markets aligns with the broader ecological literature, which highlights the co-benefits of biodiversity conservation and carbon sequestration. Portillo--Quintero et al. (2015) and Jung et al. (2021) emphasize that ecosystem integrity links biodiversity and carbon storage, supporting our observation that shocks in one domain (e.g., carbon) can amplify volatility in the other. These interdependencies, while biological in origin, are now being reflected in tokenized finance structures.

Fig. 5 presents the quantile-on-quantile net connectedness heatmap.

Fig. 5 demonstrates a quantile-dependent asymmetry in the net spillovers between the S&P 500 Biodiversity Index and the MCO2 token. Across most quantile combinations, the net connectedness values are negative, indicating that biodiversity consistently acts as a net receiver of shocks from MCO2, particularly in the mid-to-upper quantiles of biodiversity returns ($\tau= 0.6$–0.9) and the upper tail of MCO2 returns ($k = 0.9$). The strongest net spillover occurs at ($\tau= 0.6$, $k = 0.9$) with a value of –24.8, followed by other pronounced receiver states such as ($\tau= 0.6$, $k = 0.0$)= –20.3 and ($\tau= 0.9$, $k = 0.9$)= –3.9. This pattern implies that bullish trends in MCO2, potentially driven by speculative flows or a surge in carbon offset demand, can transmit volatility into biodiversity-linked assets. In contrast, positive net connectedness values, where biodiversity acts as a net transmitter, are relatively scarce and concentrated in the lower tail of biodiversity returns ($\tau= 0.1$), especially when MCO2 returns are low to moderate. For instance, ($\tau= 0.1$, $k = 0.3$)= 11.2

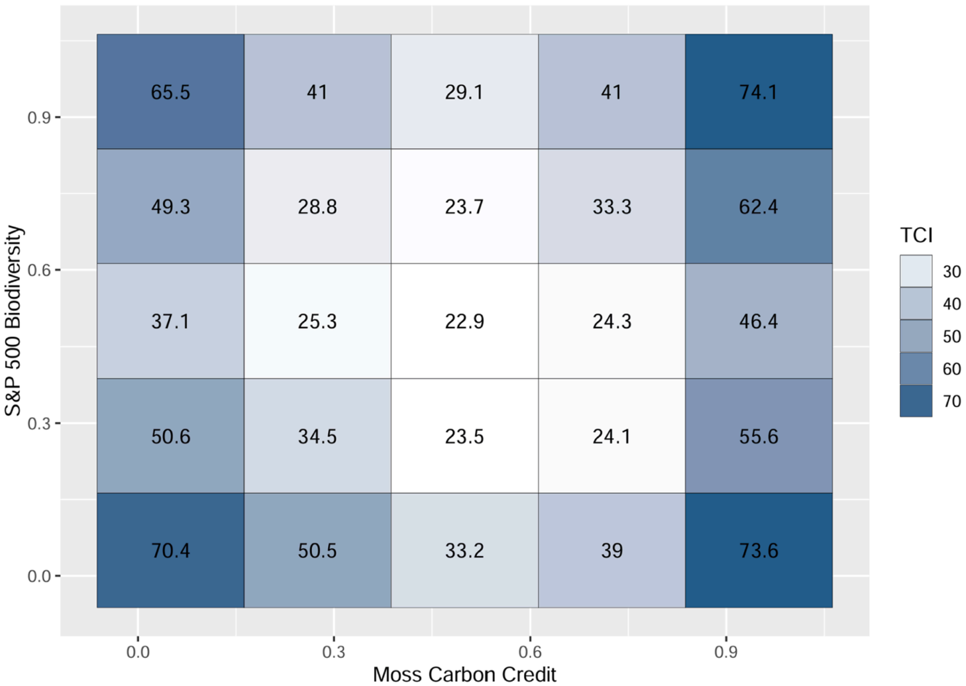

Fig. 4. Quantile-on-Quantile total connectedness index between S&P 500 biodiversity index and moss carbon credit token index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

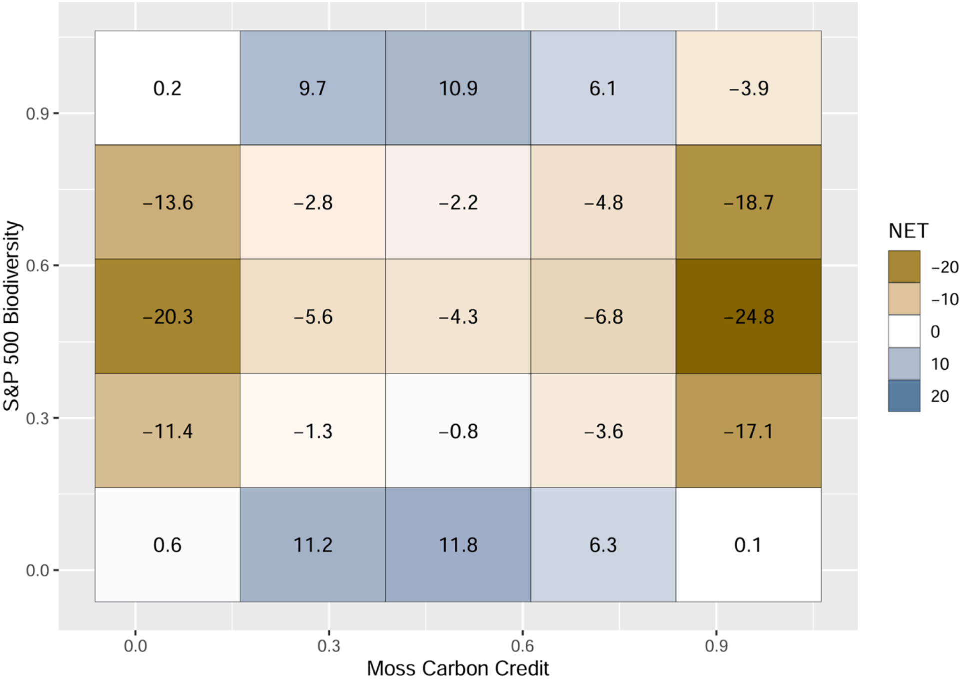

Fig. 5. Net Quantile-on-Quantile connectedness between S&P 500 biodiversity index and tokenized carbon index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

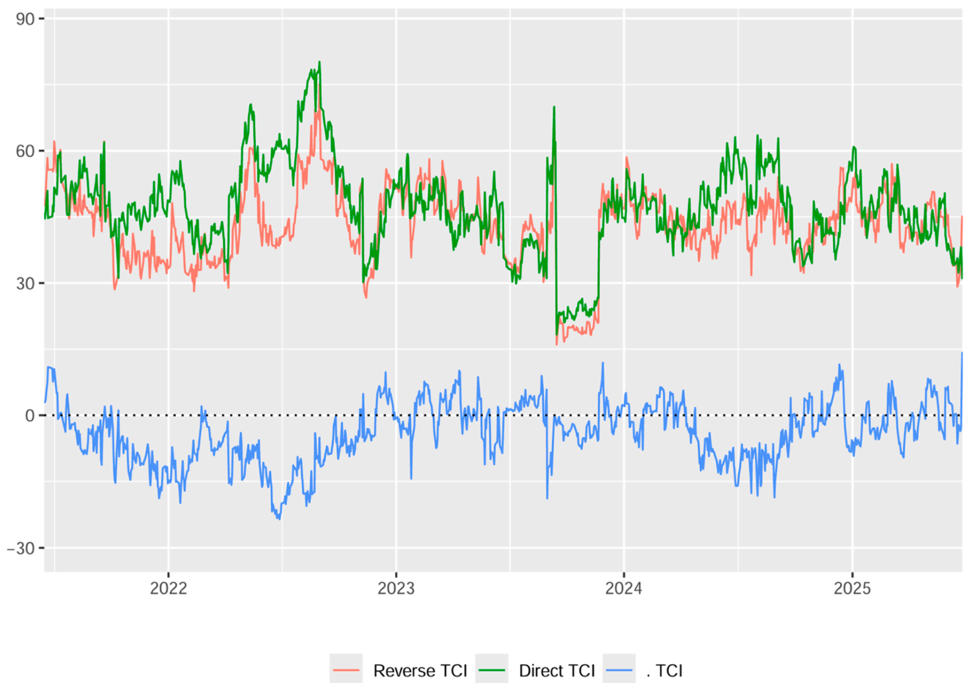

Fig. 6. Time-varying direct, reverse, and net total connectedness (ΔTCI) between S&P 500 biodiversity index and moss carbon credit token.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

and (τ= 0.1, $k = 0.6$)= 11.8. This suggests that during periods of biodiversity market stress, shocks may spill over into carbon tokens, possibly due to correlated ESG concerns, regulatory shifts, or synchronized investor responses to environmental policy risk.

Notably, there is no region with consistently high positive spillovers, indicating that biodiversity rarely dominates as a systemic volatility transmitter in this bilateral relationship. Instead, the dominance of negative spillovers in the heatmap supports the interpretation that MCO2 plays a more active role in driving systemic transmission, particularly during episodes of strong performance or tail events. These results highlight the vulnerability of biodiversity assets to upstream movements in tokenized carbon markets, raising important implications for contagion risk, portfolio hedging, and green asset interdependencies in decentralized ESG finance. The observed dominance of MCO2 as a net transmitter of shocks aligns with emerging empirical literature on biodiversity-linked financial vulnerability. Liang et al. (2024) demonstrate that exposure to biodiversity risks increases the likelihood of future stock crashes in U.S. firms, particularly due to transition risks associated with environmental regulation. In our context, this suggests that rapid movements in tokenized carbon credits, often policy-sensitive, can propagate volatility to biodiversity assets, especially during periods of regulatory change or speculative surges. Fig. 6 shows the time-varying direct, reverse, and ΔTCI between the S&P 500 Biodiversity Index and the Moss Carbon Credit Token.

Fig. 6 shows that direct TCI (green line) consistently dominates reverse TCI (red line), indicating that the S&P Biodiversity Index exerts a stronger and more persistent spillover effect on tokenized carbon markets than vice versa. The ΔTCI oscillates around the zero line, reflecting the changing dominance in shock transmission. Early and late 2023, as well as early and late 2024, show biodiversity as a net transmitter, likely reflecting increased investor attention to biodiversity-related disclosures, policy announcements, or sustainability risks spilling over into tokenized carbon markets. In contrast, several windows in mid-2022 and early 2024 see biodiversity as a net receiver, suggesting that innovations or market dynamics within the carbon credit space (e.g., changes in token liquidity, regulatory developments) influence biodiversity-linked equities. These patterns reinforce earlier heatmap findings, confirming that spillover directionality is not static but changes with market conditions. The ΔTCI trajectory demonstrates the state-contingent and bidirectional connectedness between biodiversity assets and blockchain-based sustainability instruments. This further supports the case for modeling ESG market interactions using quantile-based, time-varying approaches that capture nonlinear dependencies and dynamic leadership roles. Finally, the time-varying net spillovers between biodiversity and MCO2 align with the findings of Gao et al. (2025), who report that green finance initiatives dynamically enhance urban biodiversity in China, but with heterogeneous effects depending on local policy and market conditions. Our evidence of shifting transmission roles reinforces this complexity, highlighting how decentralized green financial instruments can alternately support or destabilize biodiversity-linked investments, depending on the broader market context.

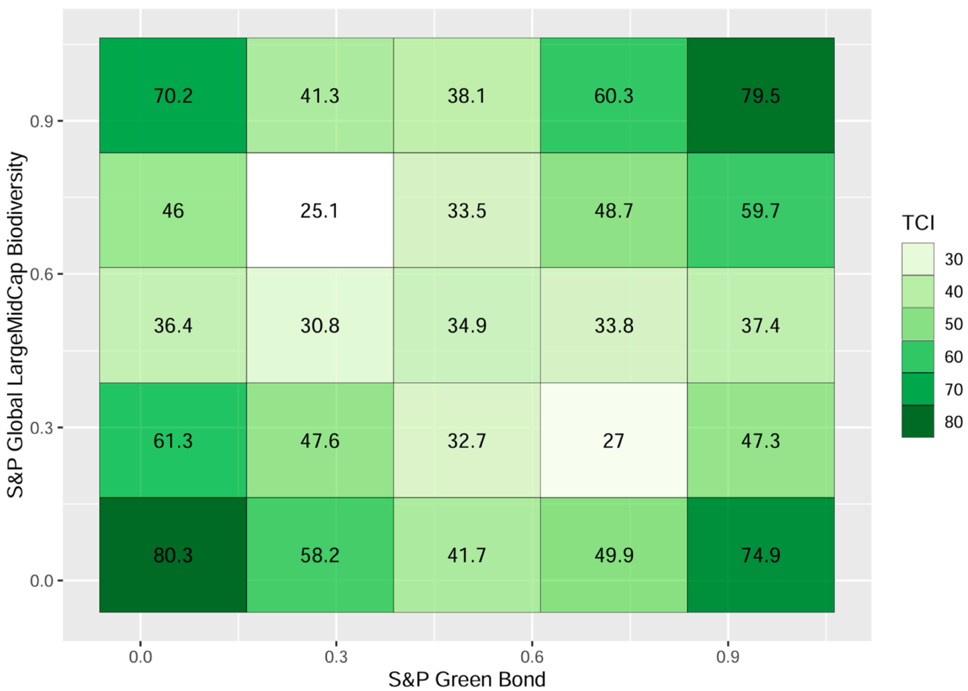

Fig. 7. Quantile-on-Quantile total connectedness index between S&P global large midcap biodiversity index and S&P green bond index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

3.3. Robustness check

Our primary analysis uses the S&P 500 Biodiversity Index to represent biodiversity-related equity exposure, due to its high data quality and focus on developed markets. To ensure robustness, we replicate the analysis using the S&P Global Large-MidCap Biodiversity Index for the same period, which provides broader geographic coverage and a diversified exposure to companies screened for biodiversity impact across both developed and emerging markets. This alternative index is constructed using S&P Global Sustainable1′s ESG and biodiversity screening criteria, ensuring conceptual consistency while allowing us to test whether our findings hold when expanding beyond a U.S.-centric equity universe.

The spillover patterns illustrated in Fig. 7 provide strong confirmation of our baseline results, as depicted in Fig. 1. The highest Total Connectedness Index (TCI) value, 80.3, is observed when both the biodiversity and green bond indices are situated in the lower quantile (τ= 0.05), closely aligning with the baseline peak of 78.4 under the same extreme condition. Likewise, a similarly elevated TCI value of 79.5 appears in the upper quantile regime (τ= 0.95), consistent with the baseline observation of 78.7, underscoring the robustness of the tail-dependent relationship. These consistent "hotspots" in the joint tails, both lower and upper, highlight the nonlinear and asymmetric nature of connectedness between biodiversity assets and green bond markets. Crucially, the recurrence of strong spillover effects across different biodiversity indices (S&P Global vs. S&P 500) reinforces the systemic role of nature-based financial instruments in shaping the dynamics of green finance. Fig. 8 shows the Quantile-on-Quantile TCI between the S&P Global Large-MidCap Biodiversity Index and the Moss Carbon Credit Token.

Fig. 8 confirms the quantile-dependent nature of connectedness observed in the primary analysis (Fig. 4), reinforcing the robustness of our findings. Specifically, the highest TCI values exceeding 70 are concentrated in the lower-left and upper-right corners of the heatmap. This suggests that joint extreme return states, whether negative or positive, lead to intensified spillovers between biodiversity equities and tokenized carbon credits. Moderate connectedness levels (TCI around 50–60) are also observed in the edges of the distribution, particularly when one of the markets lies in an extreme quantile. At the same time, the other remains in a central or moderately volatile state. In contrast, the center of the matrix (e.g., τ= 0.3–0.6, k = 0.3–0.6) consistently exhibits lower TCI values, typically ranging from 20 to 35, indicating limited interaction under average market conditions. These results are qualitatively consistent with the baseline findings in Fig. 4, indicating that the magnitude and direction of connectedness are highly sensitive to return states. The robustness check using an alternative biodiversity index confirms that the observed spillover structure is not an artifact of index selection but rather reflects a systematic and nonlinear relationship between biodiversity finance and blockchain-based carbon markets.

4. Conclusion

This study provides novel evidence on the dynamic and asymmetric connectedness between biodiversity-linked equity indices, green bond markets, and blockchain-based ESG assets using a QQ framework. By incorporating the S&P 500 Biodiversity Index, the S&P Green Bond Index, and the Moss Carbon Credit Token, we demonstrate that interlinkages in ESG financial markets are highly nonlinear, quantile-specific, and state-dependent. Both left- and right-tail regimes exhibit elevated TCI values, indicating that biodiversity-related shocks, whether negative or exuberantly positive, propagate more strongly across the ESG ecosystem.

Directional analysis suggests that biodiversity equities serve as net volatility transmitters during periods of stress or episodes focused on biodiversity policy. Regarding digital ESG assets, tokenized carbon credits (MCO2) exhibit bidirectional spillovers with biodiversity indices, where the latter transmit risk in bearish states and absorb shocks during speculative surges in the carbon token market. These findings highlight the systemic nature of biodiversity assets within the broader sustainable finance architecture. Robustness checks using the S&P Global Large-MidCap Biodiversity Index confirm the structural consistency of our results. Despite differences in geographic and capitalization scope, this broader index replicates the core spillover patterns observed in the S&P 500 Biodiversity Index, validating the reliability of quantile-based models in capturing nature-finance interdependencies.

From a policy perspective, these findings indicate the growing systemic relevance of biodiversity risks in financial markets. Regulators and central banks should recognize that biodiversity loss is an ecological crisis and a source of market instability. Policymakers can leverage these insights to strengthen disclosure mandates under frameworks like the TNFD and integrate biodiversity metrics into climate stress testing and financial stability monitoring. The amplification of connectedness during joint market extremes highlights the need for macroprudential safeguards that account for nature-related financial contagion.

For investors and asset managers, the results suggest that the benefits of diversification within ESG portfolios are highly conditional, most pronounced during tranquil periods, and significantly diminished under stress. Hence, risk management strategies should incorporate tail-dependence and quantile-specific correlations, rather than relying solely on average co-movements. Including tokenized carbon credits also introduces a new dimension to ESG portfolio construction. However, their volatile and asymmetrically linked behavior, particularly with biodiversity assets, calls for cautious integration, supported by enhanced due diligence and transparency standards in the voluntary carbon market. Future studies could expand this analysis by incorporating more biodiversity data (e.g., firm-level scores or biodiversity-themed ETFs), exploring the impact of major policy events, and examining additional blockchain-based ESG assets.

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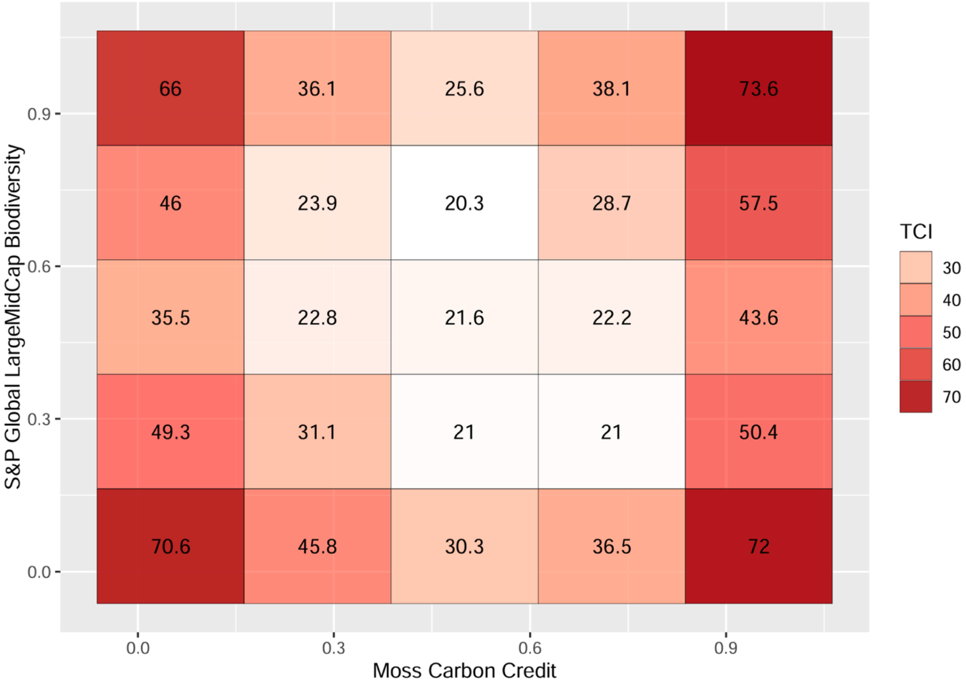

Fig. 8. Quantile-on-Quantile total connectedness index between S&P global large midcap biodiversity and moss carbon credit token index.
Note: The Quantile-on-Quantile Connectedness framework is estimated using a forecast horizon of 6 days, with a rolling window size of 60 days, and the lag length selected by the Akaike Information Criterion (AIC).

CRediT authorship contribution statement

Nader Naifar: Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Data availability

Data will be made available on request.

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