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Exploring portfolio diversification with alternative investments: An international TVP-VAR approach

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ABSTRACT

This study examines the potential for portfolio diversification across a wide range of international assets, including equities, bonds, commodities, and alternatives like gold, Bitcoin, and real estate. Using 13 years of daily returns data from over 30 countries (MSCI indices) and employing time-varying parameter vector autoregressive (TVP-VAR) approach, we provide insights into the behavior of connectedness of these assets. The results indicate that the MSCI equity indices (i.e., MSCIWO, MSCNA, MSCIEU, MSCIPC) show strong interconnectedness and global influence, while bonds exhibit bidirectional volatility with equities. Brent and BCOM drive significant spillovers, especially to NG, while BDI remains isolated. Gold acts as a hedge, linking to commodities and bonds, whereas Bitcoin remains largely disconnected from traditional markets. These findings offer practical implications for investors, funds, banks, and policymakers seeking to optimize portfolio diversification.

1. Introduction

In the ever-evolving landscape of financial markets, the construction of optimal investment portfolios remains a critical objective for portfolio managers, investors, bankers, and policymakers. Effective portfolio diversification can mitigate risks and enhance returns, yet understanding the intricate relationships between various asset classes is essential for achieving this goal. Foundational concept in investment analysis, introduced by Markowitz (1952), emphasizes the benefits of portfolio diversification, suggesting that investors can mitigate risk by holding a diversified mix of assets. To explore this hypothesis, we examine the co-movements among equities, bonds, commodities, and alternative assets. Prior research in equity markets and related assets has yielded valuable insights. For example, Paul et al. (2019) investigated the coherence between gold mining stocks, gold, and equities, finding a strong link between gold and gold mining stocks but a weaker connection with equities—particularly during financial crises like the dotcom and subprime mortgage crises. Their analysis, which utilized the Maximal Overlap Discrete Wavelet Transform (MODWT) and Continuous Wavelet Transform (CWT), was based on weekly data spanning from 1997 to 2017.

Shifting focus to BRICS countries, Qureshi et al. (2020) examined the relationship between equity funds and macroeconomic variables, using Wavelet and Granger coherence methods on data from 9005 asset management firms between 2000 and 2019. Their findings indicate that equity funds in these countries frequently lead key macroeconomic variables, highlighting complex interactions

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with important implications for portfolio strategies. In the US stock market, Bruzda (2017) provided evidence of mean reversion in industry indexes, advocating for a reclassification of industry portfolios into defensive and cyclical categories. This study employed wavelet-based tests to analyze daily and monthly US industry indexes. Additionally, Dimitriou et al. (2024) explored the effects of non-synchronous trading in G-7 equity markets, particularly during crisis periods, finding substantial impacts on volatility spillovers and underscoring the importance of data synchronization in precise market analysis. Their methodology included MA(1) adjusted return series, BEKK and DCC models, and wavelet coherence analysis. Dimitriou et al. (2013) further examined the global financial crisis, identifying contagion effects in BRICS markets following the Lehman Brothers collapse. This contagion, evidenced by heightened correlations with the USA, was analyzed using a multivariate FIAPARCH-DCC model.

Turning to the bond market, Aloui et al. (2018) found a strong connection between Sharia-compliant stocks and Islamic bond yields in the GCC. Using multiple wavelet approaches, they observed both short-term and long-term relationships, with a positive correlation in the short term and a negative one in the long term. Similarly, Nasreen et al. (2020) applied both bivariate and multivariate wavelet methods, revealing a strong correlation between GCC sukuk bond indices and Shariah stock indices. Their findings indicate a positive short-term relationship, which shifts to a negative association over the long term. Lin et al. (2018) also found that stocks and bonds are interdependent, although this relationship varies over time and is heavily influenced by market volatility and economic crises. Their results, derived from a continuous wavelet approach on data from 1988 to 2014, underscore the dynamic nature of these interactions. In contrast, Kim and In (2007) focused on G-7 countries and found no significant correlation between stock prices and yields, with wavelet correlation analysis revealing consistent results across all G-7 countries except Japan.

Other scholars have extensively investigated alternative assets, such as real estate, the Baltic Dry Index (BDI), and exotic assets. Dimitriou et al. (2020), using an FC-VAR model, found that certain alternative assets, including wine, commodities, crude oil, and the shipping index, functioned as safe havens during various crisis periods. In contrast, real estate and rare coins exhibited signs of contagion during crises, challenging the safe-haven hypothesis. In the realm of real estate, Fan and Yavas (2023) found that long-run price trends are steeper in public markets than in private markets, with cycles also lasting longer in the public market. Using a wavelet approach, they concluded that the private market led the public market until the early 1990s recession, after which the public market took the lead. Studies examining the relationship between the stock and real estate markets also reveal significant connections. Liow et al. (2019), using a wavelet approach, observed moderate integration between the housing and stock markets, characterized by scale-dependent co-movement. This interaction appears stronger over the long run, with bidirectional causal links and more pronounced return and volatility transmission effects.

Another alternative asset increasingly studied is the Baltic Dry Index (BDI). The BDI has shown connections to BRICS stock markets, though this relationship appears to fluctuate over time. Kuo et al. (2020) employed a wavelet approach, revealing a strong positive correlation between the BDI and BRICS stock markets from 2005 to 2011, especially in China and Russia. After 2011, this correlation weakened, with the BDI's influence on these stock markets shifting across different periods. The study highlights wavelet methodology as superior to traditional linear methods, such as Granger causality tests, which inadequately capture nuanced lead-lag relationships between the BDI and specific BRICS markets, particularly Brazil and South Africa. This inadequacy arises from the linear methods' assumption of constant relationships over time and their limitation to a single causal link for the entire sample period. Additionally, Angelopoulos (2017) used a wavelet approach on the BDI, identifying five distinct cycles within the low-frequency band and several high-frequency components.

Our study adds to existing literature in multiple ways. First, we utilize MSCI indices, which follow standardized procedures across markets, facilitating cross-market comparisons. A key advantage of MSCI indices is their ability to reduce synchronicity effects among international markets, making them ideal benchmark indices for global investors. Second, we employ advanced TVP-VAR analysis, which allows a detailed examination of the connectedness of our series. To our knowledge, this is the first study to explore potential international portfolio diversification benefits using this sophisticated econometric technique across such a diverse range of assets simultaneously.

Our research offers significant insights for portfolio managers, investors, bankers, and policymakers aiming to optimize portfolio construction. Specifically, our main findings can be summarized as follows: **(i)** MSCI equity indices (namely, MSCIWO, MSCNA, MSCIEU, MSCIPC) show strong interconnectedness**, ii)** bonds exhibit bidirectional volatility with equities, **iii)** Brent and BCOM drive significant spillovers, especially to NG, while BDI remains isolated. **iv)** Gold acts as a hedge, linking to commodities and bonds, whereas Bitcoin remains mainly disconnected from traditional markets.

The structure of the paper is organized as follows: Section 2 describes the data and preliminary analysis; Section 3 presents methodology. Section 4 discusses the empirical results and robustness tests; while Section 5 concludes.

2. Data and preliminary analysis

Our analysis incorporates daily data from four key asset classes: equities, bonds, commodities, and real estate. Data is sourced from Bloomberg, Federal Reserve, S&P Global and Investing.com.

For equities, we look at a number of global benchmarks: the Morgan Stanley MSCI World Equity Index (MSCIWO), which covers 23 developed equity markets; the MSCI North America Index (MSCINA), which covers the US and Canada; the MSCI Europe Index (MSCIEU), which covers large- and mid-cap stocks in 15 developed European countries; and the MSCI Pacific Index (MSCIPC), which

Table 1
Description of selected variables.

Variable	Asset class	Full Name / Description	Source
MSCIWO	Equities	MSCI World Index – 23 developed equity markets globally	Bloomberg
MSCNA	Equities	MSCI North America Index – covers US and Canada	Bloomberg
MSCIEU	Equities	MSCI Europe Index – large/mid-cap stocks in 15 European developed countries	Bloomberg
MSCIPC	Equities	MSCI Pacific Index – 5 developed Pacific region markets	Bloomberg
LEGATRUU	Bonds	Bloomberg Global Aggregate Bond Index (Unhedged)	Bloomberg
LBUSTRUU	Bonds	Bloomberg US Aggregate Bond Index	Bloomberg
LPTREU	Bonds	Bloomberg Pan-European Aggregate Bond Index	Bloomberg
BRENT	Commodities	Brent Crude Oil spot price	FRED
NG	Commodities	Natural Gas price	Investing
BCOM	Commodities	Bloomberg Commodity Index	Bloomberg
GOLD	Commodities/Alternative	Gold spot price	Bloomberg
BTC	Alternative Investment	Bitcoin Index (crypto asset)	Bloomberg
REIT	Alternative Investment	Dow Jones US Real Estate Index	S&P Global
AXX	Alternative Investment	FTSE AIM All Share Index – proxy for alternative small-cap investments	Bloomberg
BDI	Shipping/Real Economy	Baltic Dry Index – measures global shipping activity	Bloomberg

Notes: The data are derived for the following sources: https://data.bloomberg.com/, https://fred.stlouisfed.org/, https://www.investing.com/ and https://www.spglobal.com/

covers five developed markets in the Pacific region.Table 1[1] In the bond market we analyze the Bloomberg Global-Aggregate Total Return Index Value Unhedged (LEGATRUU), for the US the Bloomberg US Agg Total Return Value (LBUSTRUU) and for Europe the Bloomberg Pan-European Aggregate Total Return Index Value Un (LPTREU). Our commodities data includes Bloomberg Commodity Today (BCOM). We also track gold prices (GOLD), Brent crude oil prices (BRENT), natural gas prices (NG) and the Baltic Dry Index (BDI) for shipping. Finally, for the real estate sector, we use the Dow Jones US Real Estate Index, which represents the global real estate industry (REIT). We also use the FTSE AIM All Share Index (AXX) for alternative assets and the Bitcoin Index (BTC) for crypto. The selection of equities, bonds, commodities, and alternative assets in our study is grounded in both academic theory and practical considerations relevant to global portfolio management. These four categories form the foundation for strategic asset allocation and includes a broad spectrum of risk-return profiles, investor behaviors, and macroeconomic sensitivities.

Specifically, equities and bonds are recognized as foundational asset classes in traditional portfolio construction. Their inclusion enables the analysis of interactions between growth-oriented and income-generating investments, aligning with Markowitz (1991) seminal work on diversification. The selected commodities including oil and natural gas play a critical role in global inflation dynamics, energy markets, and broader macroeconomic cycles. They are increasingly utilized as hedging instruments in both institutional and retail portfolios (Gorton and Rouwenhorst, 2006). Also, alternative assets including gold, Bitcoin, REITs, and the Baltic Dry Index provide exposure to non-traditional sources of risk and return. These assets have attracted growing interest from investors seeking diversification beyond equities and bonds, particularly during periods of market stress (Baur and Lucey, 2010; Brière et al., 2015; Corbet et al., 2020).

In addition, the selected assets satisfy the methodological requirements of our approach, TVP-VAR and Local Gaussian Correlation, which necessitate consistent, high-frequency data over an extended period. These four asset groups offer the appropriate data structure and economic diversity to investigate dynamic connectedness and diversification potential across global markets. Our asset selection is intentionally targeted and designed to ensure both empirical robustness and practical relevance. This allows us to generate meaningful insights for investors, asset managers, and policymakers alike.

Table 1 represents a comprehensive analysis with an explanation of selected assets in our research.

The dataset includes daily returns of various asset classes from 8 December 2014–2 December 2024, giving a total of 2418 daily observations. Table 2 presents the descriptive statistics and stationarity tests. We employ the ADF test with both a constant and a constant and trend specification for returns, and we observe that all variables are stationary. This allows us to provide robust results from linear regression (OLS) for the CAPM, as well as from the TVP-VAR and Local Gaussian Correlation methods, which require stationary data

We also enhance a CAPM-type analysis (see (Dimitriou et al., 2020), to investigate the effect of the MSCI World Index (MSCIWO). The model used for estimating the CAPM relationship between alternative assets and the world financial index follows the baseline CAPM specification:

$$r(i)_t = a + \beta r(\mathrm{MSCIWO})_t + u_t \tag{1}$$

where $r(i)_t$ is the return of asset i, with i defined as a vector of alternative assets, $r(\mathrm{MSCIWO})_t$ is the return of the world financial index. The parameters α and β represent the intercept and sensitivity to the market index, respectively, u_t denotes the stochastic error term.

Table 3 shows the CAPM betas for different asset classes, indicating their sensitivity to market movements. Equities have high betas, indicating sensitivity to market changes. Among bonds, LEGATRUU (0.0414) and LPTREU (0.0397) have very low betas, reflecting

[1] See Table 1 for an explicit analysis of the dataset and its sources.

Table 2
Descriptive statistics and ADF stationarity tests.

	Mean	Median	Max.	Min.	Std. dev.	Skewness	Kurtosis	Z(t) Statistic Constant	Z(t) Statistic Constant and Trend
Equities									
MSCIWO	0.00014	0.00026	0.0365	−0.0453	0.0042	−1.063	19.081	−45.969 (0.0000)	−45.958 (0.0000)
MSCNA	0.00018	0.00026	0.0396	−0.0556	0.0049	−0.891	18.797	−51.399 (0.0000)	−51.387 (0.0000)
MSCIEU	6.65E−05	0.00029	0.0355	−0.0534	0.0046	−1.081	15.659	−46.472 (0.0000)	−46.464 (0.0000)
MSCIPC	5.00E−05	0.00016	0.0235	−0.0272	0.0041	−0.251	68.449	−44.3 (0.0000)	−44.288 (0.0000)
Bonds									
LEGATRUU	6.79E−06	4.63E−05	0.0094	−0.0095	0.0015	−0.091	63.211	−38.604 (0.0000)	−38.578 (0.0000)
LBUSTRUU	2.79E−05	7.06E−05	0.0084	−0.0090	0.0013	−0.190	68.044	−43.182 (0.0000)	−43.163 (0.0000)
LPTREU	7.07E−06	2.10E−05	0.0076	−0.0075	0.0013	0.0520	69.939	−40.678 (0.0000)	−40.659 (0.0000)
Commodities									
NG	−2.02E−05	−0.0001	0.0913	−0.1360	0.0153	−0.241	10.153	−53.39 (0.0000)	−53.364 (0.0000)
BCOM	−2.36E−05	0.0002	0.0176	−0.0228	0.0040	−0.371	54.106	−47.053 (0.0000)	−47.02 (0.0000)
BRENT	1.86E−05	0.0005	0.1789	−0.2795	0.0138	−2.703	91.354	−46.063 (0.0000)	−46.053 (0.0000)
Alternative Investments									
REIT	4.57E−05	0.0002	0.0355	−0.0831	0.0057	−1.589	29.031	−47.925 (0.0000)	−47.909 (0.0000)
AXX	4.89E−06	0.0002	0.0250	−0.0482	0.0036	−1.992	27.012	−40.517 (0.0000)	−40.528 (0.0000)
BTC	0.00099	0.0007	0.1230	−0.1329	0.0188	−0.116	80.719	−50.135 (0.0000)	−50.125 (0.0000)
GOLD	0.00014	0.0001	0.0215	−0.0254	0.0039	−0.145	59.200	−44.239 (0.0000)	−44.259 (0.0000)
BDI	5.57E−05	−0.0002	0.0883	−0.0835	0.0139	0.4642	70.010	−20.704 (0.0000)	−20.697 (0.0000)

minimal correlation with the broader market, while LBUSTRUU (-0.0026) suggests virtually no relationship. In commodities, NG (natural gas, 0.2680) and BRENT (oil, 0.9557) show different sensitivity, with oil behaving more like equities and gold (0.0780) acting as a defensive asset. Alternative assets are highly sensitive to market movements, while the Baltic Dry Index is less so. The results highlight the different risk-return profiles of asset classes, with equities and alternative assets showing greater market exposure, while bonds and commodities play a more defensive role.

3. Methodology

Antonakakis et al. (2020) improved upon the dynamic connectedness measures developed by Diebold and Yilmaz (2015) by introducing a time-varying parameter vector autoregressive (TVP-VAR thereafter) model. This approach utilizes a dynamic variance-covariance structure, allowing for better adaptability and robustness in capturing evolving relationships within financial markets.

The TVP-VAR(p) model is represented as:

$$x_t = A_t z_{t-1} + \varepsilon_t,\ \varepsilon_t \mid \Omega_{t-1} \sim N(0, \Sigma_t) \tag{2}$$

where x is the vector of endogenous variables, A denotes the matric of time-varying coefficients, z_{t-1} denotes the vector of lagged observations and Σ denotes the time-varying variance-covariance matrix

The coefficients evolve over time as follows:

Table 3
Beta estimators of a CAPM type model.

Asset	Coefficient (β)	95 % Confidence Interval
Equities		
MSCNA	1.1210***	[1.092993, 1.14905]
MSCIEU	0.7984***	[0.7351955, 0.8615378]
MSCIPC	0.4766***	[0.4256802, 0.5275249]
Bonds		
LEGATRUU	0.0414***	[0.0147155, 0.0681471]
LBUSTRUU	0.0026	[−0.0202649, 0.0254889]
LPTREU	0.0397***	[0.016931, 0.0624639]
Commodities		
NG	0.2680***	[0.1123897, 0.423575]
BCOM	0.3365***	[0.2867886, 0.386197]
BRENT	0.9557***	[0.6799082, 1.231401]
Alternative Investments		
REIT	0.9754***	[0.878566, 1.07229]
AXX	0.5178***	[0.4430835, 0.5925727]
BTC	1.0152***	[0.7499603, 1.280495]
GOLD	0.0780**	[0.0132198, 0.1426973]
BDI	−0.0249	[−0.1563097, 0.1065374]

Notes: *, **, and *** denote significance at the 10 %, 5 %, and 1 % levels, respectively

$$\mathrm{vec}(A_t) = \mathrm{vec}(A_{t-1}) + \xi_t,\ \xi_t \mid \Omega_{t-1} \sim N(0, \Xi_t) \tag{3}$$

where, ξ_t is a vector of innovations with variance-covariance matrix Ξ_t allowing the coefficients at time tt to adjust from their state at $t-1$. The recursive estimation of these coefficients is performed using the Kalman filter, which predicts and updates parameters as new data becomes available. Initial estimates for the Kalman filter are derived from a VAR model, with decay factors applied to ensure numerical stability.

To analyze the impact of shocks among variables, the TVP-VAR model is transformed into a Vector Moving Average (VMA) representation. This transformation enables the calculation of Generalized Impulse Response Functions (GIRFs):

These measure how variables respond to shocks, based on the difference between forecasts with and without a given shock.

GIRFs are represented as:

$$\mathrm{GIRF}_t(H, \delta_{j,t}, \Omega_{t-1}) = E(y_{t,H} \mid e_j = \delta_{j,t}, \Omega_{t-1}) - E(y_{t+H} \mid \Omega_{t-1}) \tag{4}$$

where H denotes the Forecast horizon and δ_j denotes Magnitude of the shock to variable j.

Generalized Forecast Error Variance Decomposition (GFEVD) quantifies how much of the forecast error variance of one variable (i) is due to shocks in another variable (j) over horizon H. It is calculated as:

$$\Phi_{ij,t}(H) = \frac{\Sigma_{h=1,J\neq i}^{H-1}\psi_{ij,t}^2(h)}{\Sigma_{i=1}^{m}\Sigma_{h=1}^{H-1}\psi_{ij,t}^2(h)} \tag{5}$$

Where $\Psi ij,t(h)$ denotes the impulse response of variable i to a shock in j at horizon h.

The Total Connectedness Index (TCI) represents the overall interconnectedness across the system, expressed as:

$$C_t(H) = \frac{\Sigma_{J=1,J\neq i}^{m}\varphi_{ij,t}(H)}{m} X \quad 100 \tag{6}$$

Directional connectedness measures the flow of shocks:

To others:

$$C_{i\rightarrow j,t}(H) = \frac{\Sigma_{J=1,J\neq i}^{m}\varphi_{ij,t}(H)}{\Sigma_{i=1}^{m}\varphi_{ij,t}(H)} X \quad 100 \tag{7}$$

From others:

$$C_{i\leftarrow j,t}(H) = \frac{\Sigma_{J=1,J\neq i}^{m}\varphi_{ij,t}(H)}{\Sigma_{i=1}^{m}\varphi_{ij,t}(H)} X \quad 100 \tag{8}$$

The net total directional connectedness identifies whether a variable is a net transmitter or receiver of shocks:

$$C_{i,t} = C_i \rightarrow {}_{j,t}(H) - C_i \leftarrow {}_{j,t}(H) \tag{9}$$

Finally, the Net Pairwise Directional Connectedness (NPDC) between two variables i and j is calculated as:

$$\mathrm{NPDC}_{ij}(H) = (\phi_{ji,t}(H) - \phi_{ij,t}(H)) \times 100 \tag{10}$$

4. Empirical results

We employ the TVP-VAR model, and the dynamic connectedness aim to analyze the spillover of volatility between assets in international portfolio analysis.

Table 4 represents the volatility connectedness between indices. The MSCIWO has a significant spillover effect on the MSCNA of 22.66 %, indicating that global market volatility has a strong impact on North American equities. This is to be expected given the large overlap in companies and economic ties between the global and North American markets. Similarly, the spillovers to the European and Asia-Pacific indices are also significant (12.83 % and 6.04 % respectively), although lower than for North America. The smaller spillovers to bond indices such as LEGATRUU, LBUSTRUU and LPTREU (around 2–3 %) suggest that bonds are less affected by equity market volatility.

The impact on commodities and shipping market (BRENT, NG, BCOM, and BDI): from MSCIWO is moderate (around 2–5 %). This suggests some contagion, but also that commodity prices are driven more by sector-specific factors than general equity market movements. Bitcoin shows only a 2.50 % spillover from MSCIWO. This highlights its nature as a non-traditional asset that may not fully conform to traditional financial market behavior. Similarly, gold's spillover from MSCIWO is modest at 1.85 %, reinforcing its status as a potential safe-haven asset that does not closely follow stock market volatility. Finally, a higher spillover is observed for the real estate index (13.22 %) and alternative investments (12.69 %). Similar results are observed for the North American and European equity markets, which is consistent with their high degree of financial integration. In contrast, the Asia-Pacific equity index shows less spillover to global and other regional equity indices, possibly reflecting financial market segmentation. This finding aligns with prior studies (e.g., (Shan et al., 2022), which noted lower volatility transmission from Asian markets, especially during non-crisis periods.

Table 4
Spillover connectedness analysis.

	MSCIWO	MSCNA	MSCIEU	MSCIPC	LEGATRUU	LBUSTRUU	LPTREU	BRENT	NG	BCOM	REIT	AXX	BTC	GOLD	BDI	FROM
MSCIWO	24.69	22.66	12.83	6.04	2.08	2.46	1.30	2.33	0.75	3.38	9.01	7.34	2.50	1.85	0.78	75.31
MSCNA	25.05	27.36	10.15	3.62	2.13	2.74	1.15	2.12	0.88	2.89	10.47	5.95	2.72	1.98	0.79	72.64
MSCIEU	16.20	12.34	29.48	4.84	3.61	2.86	2.06	2.76	0.84	3.13	5.33	11.78	1.80	2.10	0.87	70.52
MSCIPC	15.26	12.31	10.08	26.89	3.56	2.80	1.66	2.39	0.89	4.18	5.52	8.27	2.53	2.54	1.13	73.11
LEGATRUU	3.27	3.18	4.27	2.73	34.66	18.76	9.45	1.41	1.02	1.93	3.43	2.79	1.43	10.60	1.07	65.34
LBUSTRUU	3.38	3.42	3.21	1.61	19.78	36.84	12.69	2.15	0.96	1.44	3.58	2.20	1.04	6.75	0.93	63.16
LPTREU	2.36	1.97	2.80	1.56	12.61	15.81	46.01	1.93	1.20	1.95	3.88	1.94	1.16	3.37	1.48	53.99
BRENT	4.50	3.86	4.30	2.35	1.63	2.57	1.89	47.73	1.57	18.66	1.85	3.38	1.80	2.51	1.39	52.27
NG	2.28	2.51	1.79	1.40	1.84	1.78	1.54	1.87	64.95	11.05	2.11	2.19	1.35	1.55	1.78	35.05
BCOM	5.58	4.43	4.01	3.57	1.93	1.69	1.55	15.24	7.25	39.84	2.41	3.72	2.12	5.73	0.93	60.16
REIT	13.22	14.19	5.62	2.37	3.21	3.88	3.19	1.49	1.27	2.01	39.81	3.74	2.23	2.46	1.31	60.19
AXX	12.69	10.70	13.27	6.13	2.64	2.40	1.68	2.64	1.08	3.22	4.91	33.19	2.40	1.94	1.12	66.81
BTC	5.06	4.99	2.94	2.83	2.30	1.63	1.57	2.20	1.45	2.62	3.17	3.39	61.41	2.58	1.87	38.59
GOLD	3.35	3.28	3.12	2.73	12.26	8.31	3.10	2.34	1.18	6.54	2.91	2.41	2.44	44.47	1.59	55.53
BDI	2.26	2.00	1.93	2.58	1.88	1.62	1.78	1.77	1.77	1.64	2.05	2.08	1.51	1.95	73.17	26.83
TO	114.44	101.83	80.34	44.37	71.44	69.31	44.60	42.63	22.11	64.66	60.63	61.17	27.02	47.91	17.03	869.50
Inc.Own	139.13	129.19	109.82	71.26	106.10	106.15	90.61	90.36	87.06	104.50	100.44	94.36	88.43	92.38	90.20	cTCI/TCI
NET	39.13	29.19	9.82	−28.74	6.10	6.15	−9.39	−9.64	−12.94	4.50	0.44	−5.64	−11.5	−7.62	−9.80	62.11/57.97
NPT	14.00	13.00	12.00	4.00	8.00	10.00	4.00	5.00	1.00	8.00	10.00	9.00	0.00	5.00	2.00	

Notes: The terms “FROM” and “TO” indicate the source and destination of causal impacts between variables, respectively. Positive values of NET signify that a variable is a net transmitter of spillover effects, while negative values indicate it is a net receiver. The numbers range from 0 to 100, representing percentages that show how much of a variable’s variance is attributed to itself (diagonal values) or to other variables (off-diagonal values). The NPT (Net Pairwise Transmission) in the table offers an ordinal ranking of each variable based on its net spillover role.

The bond markets show limited spillovers to equity markets, suggesting that although both asset classes are affected by similar macroeconomic factors (such as interest rates and inflation), their volatility channels do not strongly influence equity markets. This pattern of limited spillovers between equity and bond volatility is supported by a large body of literature that views bonds as a diversification tool in mixed-asset portfolios (see (Campbell and Viceira, 2002), for example). However, there is strong interaction between different bond markets, highlighting the role of global interest rate expectations and economic policies in shaping bond market dynamics. The impact of bond volatility on commodities, bitcoin, and gold is also minimal, underscoring their role as generally stable asset classes with limited internal volatility effects. Gold and bitcoin are commonly regarded in the literature (see (Baur and Lucey, 2010; Corbet et al., 2018), among others) as hedges against financial or monetary shocks, due to their non-correlated or weakly correlated nature with traditional financial assets.

Commodities such as Brent and natural gas show significant internal dynamics that impact the broader commodity index. This outcome suggests that energy commodities play a dominant role in shaping commodity market volatility (i.e., this is a trend observed also by Kilian and Park (2009). Meanwhile, bitcoin's spillover into other financial assets is very limited, highlighting its status as a distinct, stand-alone asset class. Its volatility does not significantly affect traditional financial markets, supporting the view of bitcoin as a separate asset class with unique speculative drivers and investor profiles.

Gold shows minimal spillovers to other asset classes, confirming its role as a safe haven. During periods of high volatility in other markets, gold's stable or even negative correlation can provide a diversification benefit. Both REITs and the AXX show a moderate to high sensitivity to equity market volatility, particularly North American equities. REITs and AXX show lower spillovers between each other, suggesting that while they are influenced by similar factors, their internal market dynamics are different. The BDI, an indicator of shipping costs, shows almost no spillover to or from other asset classes, highlighting its specialized nature and limited relevance to broader financial market volatility.

We present the results from Table 3 in graphical form. The central role played by the MSCI equity indices (MSCIWO, MSCNA, MSCIEU, MSCIPC), which show significant interconnectedness and influence on each other and on global markets. Bonds (LEGATRUU, LBUSTRUU, LPTREU) also show notable interactions with equity markets, suggesting a bidirectional transmission of volatility. The commodity sector, in particular Brent and the broader commodity index (BCOM), is influential, with strong spillovers to other commodities such as natural gas (NG). Conversely, the Baltic Dry Index (BDI) remains relatively isolated, highlighting its limited impact on other financial markets. Gold and bitcoin show specific patterns, with gold acting as a hedge and showing links mainly to commodities and bonds, while bitcoin remains somewhat disconnected, reflecting its nascent integration with traditional financial markets.

4.1. *Robustness analysis using local Gaussian correlations*

The Local Gaussian Correlation method (Tjøstheim and Hufthammer, 2013) is employed to ensure robust results. This method offers several advantages, including its ability to capture local variations, making it ideal for analyzing non-linear relationships and adapting to changing market volatility. It is based on a strong theoretical foundation that ensures existence, uniqueness and limits, and can be used to analyze non-Gaussian contexts, enabling insights into complex financial data (see Fig. 1).

Studies have used this method to analyze dynamic correlations (see (Bampinas and Panagiotidis, 2017; Bampinas et al., 2023; Dimitriou et al., 2024). We present our results in Fig. 2.

Our study confirms the methodology, showing a strong linear relationship between MSCIWO and other markets. The results are particularly pronounced in North America and Europe, while the Asia-Pacific region exhibits a comparatively lower positive connectedness. Additionally, we observe a near-zero correlation with bond indices, characterized by a non-linear dependence within the US region. Brent and BCOM exhibit a linear correlation range of 0.029 and 0.35, respectively. The REIT and AXX indices exhibited a

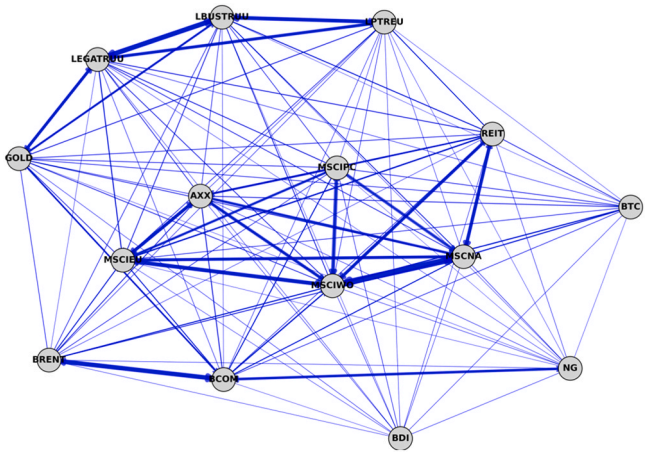

Fig. 1. Graphical analysis of dynamic connectedness.

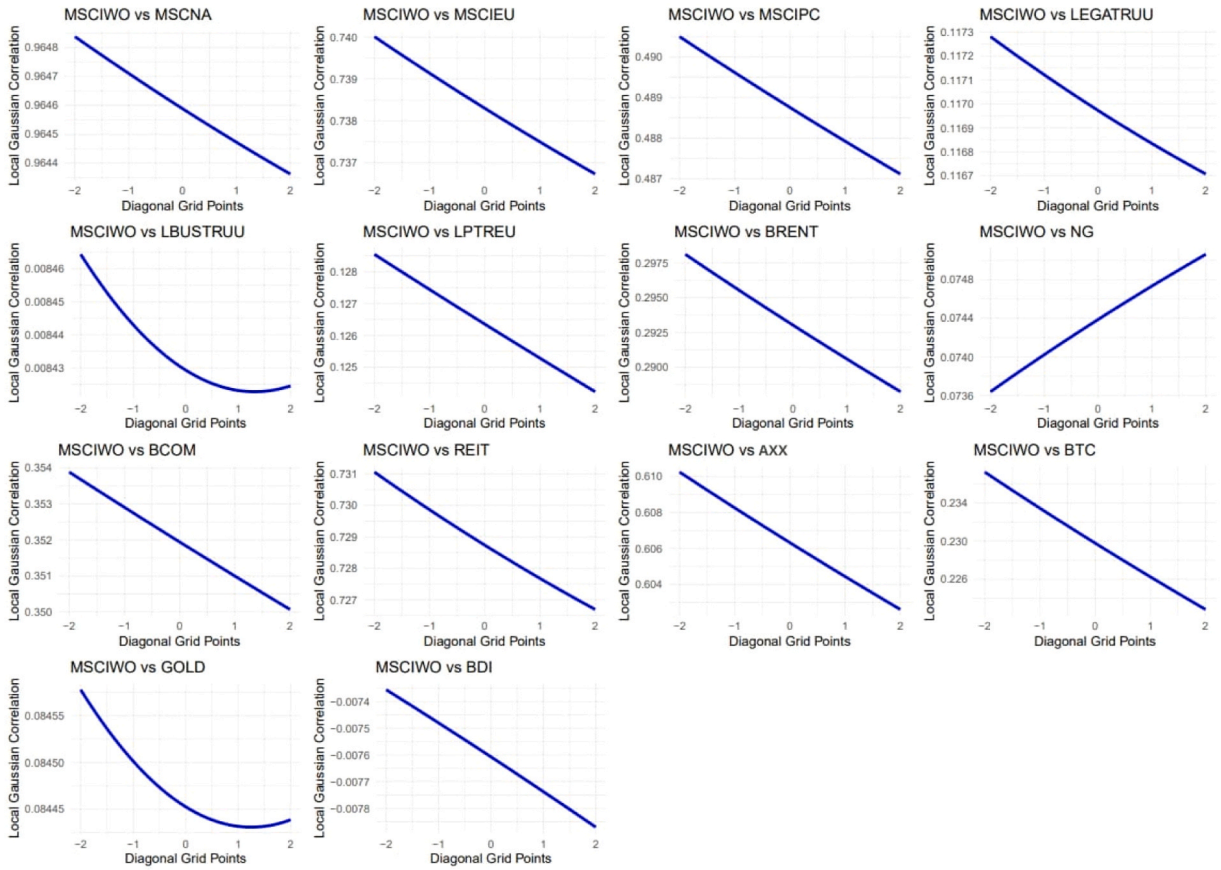

Fig. 2. Local Gaussian correlations.

higher and linear correlation with the primary results. The correlation with NG and Gold was negligible. BTC ranged from 0.22 to 0.23, and BDI indicated a negative correlation, thereby verifying the opposite direction of market volatility. The study's findings highlight linear relationships that investors should consider when selecting their portfolios.

5. Conclusions

The study offers an in-depth examination of the connectedness across global financial markets and various asset classes, emphasizing the importance of portfolio diversification. It reveals significant interconnectedness among these asset classes over a long timeline (i.e., 2014–2024), highlighting the critical role of diversified investment strategies in managing portfolio risk.

Our main results indicate that the MSCI equity indices (MSCIWO, MSCNA, MSCIEU, MSCIPC) play a central role, exhibiting strong interconnectedness and significant influence on global markets. These findings support their leading role in transmitting market volatility globally. Bond markets (LEGATRUU, LBUSTRUU, LPTREU) show bidirectional volatility transmission with equities, suggesting only minor diversification benefits between them. The commodity sector, particularly BCOM, exhibits substantial spillovers to natural gas (NG), while Brent's influence on NG is limited—indicating potential diversification benefits between these commodities. The Baltic Dry Index (BDI) is relatively isolated, with minimal impact on other markets, thus acting as a potential hedge.

Gold continues to function as a hedge, primarily connected to commodities and bonds, while Bitcoin remains relatively disconnected—reflecting its early stage of integration into traditional financial markets. This contributes to the ongoing debate on whether Bitcoin can be considered the new digital gold and whether it can serve as a hedge or an effective diversifier. In other words, gold still offers stronger hedging properties for portfolio managers compared to Bitcoin; however, Bitcoin may potentially be used as a diversifier.

In conclusion, the study extends the foundational principle of diversification in portfolio management by highlighting the complex and dynamic connectedness among different asset classes. The findings advocate for a dynamic and responsive approach to portfolio construction, especially during periods of volatility, offering valuable guidance for investors seeking robust, well-diversified investment strategies. This contribution to the field is significant, offering both theoretical and practical implications for effective investment management in an evolving global economic landscape.

CRediT authorship contribution statement

Alexandros Tsioutsios: Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dimitrios Dimitriou:** Writing – original draft, Visualization, Supervision, Software, Methodology, Data curation, Conceptualization. **Larisa Yarovaya:** Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization.

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.

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Data availability

Data will be made available on request.

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