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Effect of options "Americanization" reform on underlying market dynamics: a multifractal analysis

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Introduction: This paper investigates the effect of a major institutional reform on the Shanghai Futures Exchange: the change in the exercise style of its gold futures option contracts from European to American ("Americanization" reform). We aims to examine the reform's impact on the efficiency of the gold futures market (the underlying of gold futures options) and the complexity of the cross correlation between gold futures and spot markets.
Methods: The Multifractal Detrended Moving-Average Cross-Correlation Analysis (MF-X-DMA) method is employed in this study. Additionally, the nonlinear Granger test is used to assess the directional predictive relationship between the gold futures and spot markets.
Results: The MF-X-DMA results indicate that the "Americanization" reform improves the efficiency of the gold futures market but increases the complexity of the cross correlation between gold futures and spot markets. Moreover, the nonlinear Granger test shows that the unidirectional predictive lead from the futures to the spot market diminishes after the reform.
Discussion: Our findings suggest that the price discovery function transitions from a simple leader-follower model to a more sophisticated, synchronized system. This study contributes to related literature by providing empirical evidence on the market effects of different option exercise styles from the multifractal perspective.

KEYWORDS

option exercise style, MF-X-DMA, multifractality, market efficiency, gold futures

1 Introduction

The exercise style of an option contract is a fundamental characteristic, playing an important role in determining pricing models, trading strategies, and risk management frameworks for investors. While both American- and European-style options are widely traded globally, they offer distinct risk-return profiles and hedging requirements. Theoretically, such a fundamental difference in derivative design should have a different effect on the price behavior of the underlying asset. However, existing literature [1–4] primarily focuses on the valuation and pricing models for these two option types, while their potentially different impacts on the underlying asset's market dynamics has received limited attention. This research gap exists largely because of the institutional rigidity of option markets, i.e., exchanges and regulators typically decide on an exercise style when a product is launched, and it is rarely changed afterward.

The recent institutional change in China's derivatives market offers a unique opportunity to fill this literature gap. On July 31, 2020, the Shanghai Futures Exchange (SHFE) announced a significant decision to change the exercise style of its existing gold (and copper) futures options from European to American (hereafter referred to as the "Americanization" reform), in order to provide market participants with more flexible and efficient risk-management tools. As American options allow holders to exercise at any point and offer superior hedging capabilities against adverse price movements, such an "Americanization" reform is expected to enhance the attractiveness and functionality of the gold futures options market, boost liquidity, and better serve the real economy's hedging needs. The reform was officially implemented on November 16, 2021. The announcement also outlined a transitional period, where both European and American style options would co-exist until November 2022, after which the market would fully transition to the American style. This rare and significant event allows for a clear before-and-after analysis of how a structural shift in the derivatives market (specifically, the move toward a more flexible and complex option type) affects the price dynamics and efficiency of its underlying asset.

To thoroughly analyze the impact of this "Americanization" reform, this study uses the Fractal Market Hypothesis (FMH) as a framework. It is widely documented that financial asset returns exhibit complex statistical properties, such as fat tails, long-range memory, and scale-dependent correlations, which are characteristics of multifractal processes [5–13]. These features mean that traditional models based on the assumption of random walks are not sufficient for a complete analysis. The evolution of econophysics has provided a sophisticated toolkit to address this challenge. Early methods like the Detrended Fluctuation Analysis (DFA) [14], the Multifractal Detrended Fluctuation Analysis (MF-DFA) [15], and the Detrended Cross-Correlation Analysis (DCCA) [16] offer ways to quantify the degree of multifractality in a single time series as a proxy for market inefficiency. These methods are later extended to a bivariate context with the development of methods such as the Multifractal Detrended Cross-Correlation Analysis (MF-DCCA) [17], and the Multifractal Detrended Moving-Average Cross-Correlation Analysis (MF-X-DMA) [18]. These methodologies are widely used to investigate the cross-correlations among financial markets [5–8, 19, 20].

Among these methods, the MF-X-DMA method is well-regarded for its robustness in removing local trends from non-stationary financial time series [8, 10, 19, 21]. Therefore, we use the MF-X-DMA framework to investigate the effect of the "Americanization" reform on underlying market dynamics. We first analyze the impact on the internal efficiency of the gold futures market (i.e., the underlying market of gold futures options) itself. We find that the market becomes significantly more efficient after the "Americanization" reform, evidenced by a marked reduction in its degree of multifractality. In addition, we examine the reform's impact on the external price discovery function by assessing the cross-correlation between the futures and spot markets. Results show that the simple linear correlation between the two markets becomes weaker, yet their non-linear, multifractal relationship intensifies. Finally, the non-linear Granger causality test reveals that the unidirectional lead that the futures market held over the spot market before the reform completely disappears afterward, suggesting a fundamental shift to a more synchronized pricing model.

This study contributes to the literature in several ways. First, it offers fresh empirical insights into the microstructural impact of a specific but important institutional reform (specifically, the change in option exercise style) from the perspective of a major emerging market. While option pricing theories are well-developed, empirical studies on the real-world effects of such institutional reforms are quite limited. Our research utilizes a unique natural experiment to address this crucial gap between derivative theory and market reality.

Second, we provide a more nuanced understanding of market maturation. We present a seemingly paradoxical result, i.e., increased market efficiency is coupled with a more complex inter-market relationship and the disappearance of lagged predictability. Our findings suggest that as markets become more efficient and integrated, price discovery transitions from a simple, lagged leader-follower model to a highly complex, synchronized system where information is reflected almost instantaneously across markets.

Third, we contribute methodologically by presenting an integrated framework for evaluating the multifaceted impacts of financial regulations. By combining multifractal analysis with a nonlinear causality test, we provide a more comprehensive framework than traditional linear event studies. This approach provides a deeper understanding of how regulations reshape market efficiency, complexity, and information flow.

The rest of this paper is structured as follows. Section 2 details our methodological framework, including the MF-X-DMA method and the non-linear Granger causality test. Section 3 describes the data and provides descriptive statistics. Section 4 presents the empirical results on the transformation of market efficiency. Section 5 analyzes the reshaping of the price discovery function. Finally, Section 6 concludes the paper.

2 Methodology

Following related literature [5, 8, 10, 12, 22–25], this paper empirically assesses the impact of the "Americanization" reform by employing a two-stage methodological framework designed to capture the complex, non-linear dynamics characteristic of financial markets. First, we utilize the MF-X-DMA method introduced by Jiang and Zhou [18] to quantify the evolving complexity within the gold futures market and in its interaction with the spot market. Second, to identify the directionality of information flow, a question central to the price discovery function, we use a nonlinear Granger causality test proposed by Baek and Brock [26]. This combination facilitates a robust investigation that moves beyond the limitations of traditional linear models [8, 27, 28].

2.1 MF-X-DMA

The MF-X-DMA method is a powerful tool for analyzing multifractal properties in non-stationary time series, with a notable advantage in its use of moving averages for trend removal [8, 19, 21]. The analysis begins with the conversion of the daily logarithmic return series $\{x_k\}$ and $\{y_k\}$ with length of N into cumulative profiles, $X(t)$ and $Y(t)$, defined by Equations 1, 2, respectively.

$$X(t) = \sum_{k=1}^{t} (x_i - \bar{x}) \tag{1}$$

$$Y(t) = \sum_{k=1}^{t} (y_k - \bar{y}) \tag{2}$$

where $t = 1, 2, \ldots, N$; and $\bar{x}$ and $\bar{y}$ are the means of the respective full series. This integration transforms the stationary return series into random walk-like profiles suitable for fluctuation analysis. These profiles are then partitioned into $N_s = \text{int}(N/s)$ non-overlapping segments of length s, with the process repeated from the end of the series to produce a total of $2N_s$ segments.

For each segment v, the local trend is removed by subtracting its corresponding moving average, $\tilde{X}_v(j)$ and $\tilde{Y}_v(j)$. The detrended covariance for each segment is then calculated by Equation 3.

$$F^2(s,v) = \frac{1}{s}\sum_{j=1}^{s} [X((v-1)s+j) - \tilde{X}_v(j)][Y((v-1)s+j) - \tilde{Y}_v(j)] \tag{3}$$

The qth order fluctuation function, $F_{xy}(q,s)$, is obtained by averaging these segmental covariances over all $2N_s$ segments. For any real $q \neq 0$, it is defined by Equation 4.

$$F_{xy}(q,s) = \left\{ \frac{1}{2N_s} \sum_{v=1}^{2N_s} [F^2(s,v)]^{q/2} \right\}^{1/q} \tag{4}$$

For the special case of $q = 0$, the function is calculated via a logarithmic average to avoid divergence as shown in Equation 5.

$$F_{xy}(0,s) = \exp\left\{ \frac{1}{4N_s} \sum_{v=1}^{2N_s} ln[F^2(s,v)] \right\} \tag{5}$$

The fluctuation function $F_{xy}(q,s)$ is expected to scale with the segment size s as a power-law, formalized by Equation 6.

$$F_{xy}(q,s) \sim s^{H_{xy}(q)} \tag{6}$$

The generalized Hurst exponent for the cross-correlation, $H_{xy}(q)$, is estimated via a log-log linear regression of $F_{xy}(q,s)$ against s. A non-constant $H_{xy}(q)$ as a function of q signals the presence of multifractality in the cross-correlation.

From the generalized Hurst exponent, we derive the multifractal spectrum $f(\alpha)$ through a Legendre transform, which provides a richer description of the underlying scaling structure. First, the mass scaling exponent $\tau(q)$ is calculated from $H_{xy}(q)$ as defined in Equation 7.

$$\tau(q) = qH_{xy}(q) - 1 \tag{7}$$

A non-linear relationship between $\tau(q)$ and q is a direct confirmation of multifractality. The singularity strength, α, which represents the local scaling behavior, is the first derivative of $\tau(q)$, as shown in Equation 8.

$$\alpha(q) = \frac{d\tau(q)}{dq} = H_{xy}(q) + q\frac{dH_{xy}(q)}{dq} \tag{8}$$

Finally, the multifractal spectrum $f(\alpha)$, representing the fractal dimension of the subset of the series characterized by the exponent α, is computed by Equation 9.

$$f(a) = q\alpha(q) - \tau(q) = q\alpha(q) - \left(qH_{xy}(q) - 1\right) \tag{9}$$

The shape and width of the $f(\alpha)$ vs. α spectrum graphically illustrate the nature and degree of multifractality. To quantify this, we compute several key metrics. The primary measure is the width of the multifractal spectrum as defined by Equation 10.

$$\Delta a = \alpha_{max} - \alpha_{min} \tag{10}$$

where $\alpha_{\max}$ and $\alpha_{\min}$ correspond to the values at the minimum and maximum of the tested q-range, respectively.

A complementary metric is the range of the generalized Hurst exponent itself, calculated by Equation 11.

$$\Delta H = H_{xy}(q_{min}) - H_{xy}(q_{max}) \tag{11}$$

Lastly, we utilize the Magnitude of Long Memory (MLM) index, also referred to as the Market Deficiency Measure, which provides a single, normalized value [8, 29, 30]. Specifically, MLM is computed by Equation 12.

$$MLM = \frac{1}{2}\left[\left|H_{xy}(q_{min}) - 0.5\right| + \left|H_{xy}(q_{max}) - 0.5\right|\right] \tag{12}$$

Accordingly, a larger $\Delta\alpha$, ΔH, or MLM indicates a higher degree of multifractality. In the context of cross-correlations between two series, x and y, a larger $\Delta\alpha$, ΔH, or MLM signifies a higher degree of multifractality in their relationship, indicating that their co-movement is more complex, non-linear, and dynamically unstable, rather than being a simple, constant correlation.

In the specific case of a single market analysis (i.e., $x = y$), these metrics function as well-established proxies for market inefficiency. Higher values for these indicators signify a stronger degree of multifractality, reflecting greater long-range dependence and a more significant deviation from the random walk behavior predicted by the Efficient Market Hypothesis. Consequently, a higher value for these metrics implies a lower level of market pricing efficiency.

2.2 Nonlinear granger causality test

While MF-X-DMA quantifies the complexity of market relationships, it does not establish causality. To examine the direction of information flow, we employ the nonlinear Granger causality test proposed by Baek and Brock [26]. This non-parametric approach is essential for detecting predictive relationships in the complex and non-linear market environment [5, 8, 23, 31].

Let $\{X_t\}$ and $\{Y_t\}$ be two return series. The test's null hypothesis is that the past of Y does not contain additional information that helps predict the future of X, beyond the information already contained in the past of X. Let X_t^m denote the m-length lead vector of X, and $X_{t-L_x}^{L_x}$ and $Y_{t-L_y}^{L_y}$ be the lag vectors of length L_x and L_y, respectively. The null hypothesis of non-causality can be expressed in terms of conditional probabilities for a distance $\varepsilon > 0$ as shown in Equation 13.

$$\begin{aligned} &Pr\left(\|X_t^m - X_s^m\| < \varepsilon \mid \left\|X_{t-L_x}^{L_x} - X_{s-L_x}^{L_x}\right\| < \varepsilon, \left\|Y_{t-L_y}^{L_y} - Y_{s-L_y}^{L_y}\right\| < \varepsilon\right) \\ &= Pr\left(\|X_t^m - X_s^m\| < \varepsilon \mid \left\|X_{t-L_x}^{L_x} - X_{s-L_x}^{L_x}\right\| < \varepsilon\right) \end{aligned} \tag{13}$$

where $\|\cdot\|$ denotes the maximum norm. This states that the probability of two future paths of X being close is independent of the past paths of Y. This equality is operationally tested by comparing the ratios of corresponding correlation integrals, which estimate the joint probabilities of the vector systems being within the distance ε. Let C1, C2, C3, and C4 denote the various joint probability estimates. The test statistic is formulated based on the difference between these ratios as shown in Equation 14.

$$\sqrt{n}\left(\frac{C1\left(m+L_x,L_y,\varepsilon\right)}{C2\left(L_x,L_y,\varepsilon\right)}-\frac{C3\left(m+L_x,\varepsilon\right)}{C4\left(L_x,\varepsilon\right)}\right)\xrightarrow{d}N\left(0,\sigma^2\right) \quad (14)$$

where n is the number of observations. A statistically significant value of this test statistic leads to the rejection of the null hypothesis, providing evidence of a non-linear Granger causal flow from Y to X. By applying this test in both the (Futures return → Spot return) and (Spot return → Futures return) directions, we can rigorously assess how the price discovery leadership is affected by the reform.

3 Data and descriptive statistics

3.1 Data and sample period

We focus on the potential effect of the "Americanization" reform on the underlying market's efficiency as well as its price discovery function. The gold futures contract data is sourced from the Shanghai Futures Exchange (SHFE), while the gold spot price data, specifically for the AU9999 contract, is obtained from the Shanghai Gold Exchange (SGE). The AU9999 contract is the most actively traded spot gold contract in China and serves as the primary benchmark for the domestic physical gold market.

Although the "Americanization" reform of gold futures options officially took effect on November 16, 2021, there was a transition period where both European and American style options co-existed, lasting until November 2022. To ensure a clear comparison and avoid confounding effects from this transition phase, we exclude the period from November 16, 2021 to November 30, 2022, from our sample. Consequently, our full sample is divided into two distinct sub-periods with a similar number of observations: (1) the pre-reform period, from May 1, 2019, to November 15, 2021; and (2) the post-reform period, from December 1, 2022, to May 30, 2025.

To analyze the market dynamics, we follow related literature [9, 32–34] and calculate the logarithmic returns for both series using Equation 15.

$$R_t = \ln\left(P_t\right) - \ln\left(P_{t-1}\right) \quad (15)$$

where P_t is the closing price on day t. For the gold futures data, we address the issue of contract expiration by constructing a continuous futures return series. Specifically, we follow related literature [35–37] and identify the dominant contract each day as the one with the highest trading volume (meaning it is the most actively traded). We then move to the next dominant contract before the current one expires. This creates a continuous time series of futures returns that reflects the most liquid segment of the market where price discovery is concentrated, thereby avoiding potential biases from the low liquidity and pricing anomalies often present in non-dominant contracts, especially near their expiration.

TABLE 1 Descriptive statistics of daily gold futures and spot returns.

Period	Mean	Std	Skew	Kurt	Jarque-bera
Panel A: Gold futures return					
Pre-reform period	0.0013	0.0217	−0.5777	4.5514	94.4804***
Post-reform period	0.0022	0.0187	0.4744	4.7503	95.6280***
Panel B: Gold spot return					
Pre-reform period	0.0005	0.0102	−0.3710	7.2390	467.6220***
Post-reform period	0.0011	0.0092	−0.4888	6.6580	345.8712***

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after. "Mean," "Std.," "Skew," and "Kurt" denote Mean, Standard Deviation, Skewness, and Kurtosis, respectively. "Jarque-Bera" is the statistic for the Jarque-Bera test, with "***" indicating significant at the 1% level.

3.2 Descriptive statistics

Table 1 summarizes the descriptive statistics for the return series of both gold futures and spot in the pre- and post-reform periods. As shown, the return series exhibit several stylized facts common to financial assets [38–40]. The mean daily returns for both futures and spot are close to zero across both sub-periods. More importantly, all series exhibit significant non-Gaussian characteristics. The kurtosis values for both futures and spot are greater than 3, indicating that the return distributions are highly leptokurtic and possess "fat tails," which points to a higher chance of extreme price movements compared to a Gaussian model. Furthermore, the skewness values are generally non-zero, suggesting asymmetry in the return distributions. The Jarque-Bera test statistics are large and highly significant ($p < 0.01$) for all return series, formally rejecting the null hypothesis of normality.

These characteristics pose challenges for traditional linear models [28, 41]. These characteristics justify our choice of methodological framework, as multifractal analysis is well-suited to characterize the complex scaling properties and long-range dependence inherent in such data.

4 Effect of the "Americanization" reform on underlying market efficiency

4.1 Change in the degree of multifractality

We first investigate the scaling properties of the gold futures (i.e., the underlying asset of options affected by the reform) return series by examining the generalized Hurst exponent, $H(q)$. Accordingly, the behavior of $H(q)$ as a function of the moment q would indicate not only the presence of multifractality but also the nature of persistence in fluctuations of different magnitudes. Table 2 presents

TABLE 2 Generalized Hurst exponent *H*(*q*) for gold futures returns.

q	Pre-reform period	Post-reform period
−10	0.8663	0.8639
−9	0.8543	0.8533
−8	0.8397	0.8404
−7	0.8214	0.8250
−6	0.7981	0.8068
−5	0.7689	0.7863
−4	0.7337	0.7647
−3	0.6955	0.7439
−2	0.6591	0.7242
−1	0.6262	0.7038
0	0.5962	0.6803
1	0.5686	0.6538
2	0.5438	0.6270
3	0.5221	0.6028
4	0.5034	0.5820
5	0.4873	0.5647
6	0.4734	0.5501
7	0.4612	0.5376
8	0.4505	0.5268
9	0.4411	0.5173
10	0.4329	0.5089

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after.

the estimated $H(q)$ values for a range of q from −10 to 10, a range widely adopted in the literature as it is sufficient to capture the full spectrum of scaling behaviors, from small fluctuations (negative q) to large shocks (positive q).

As shown in Table 2, there exists a clear dependence of $H(q)$ on q in both periods. In theory, for a monofractal series, $H(q)$ would be a constant value for all q. However, our results show that $H(q)$ is a distinctly decreasing function of q, confirming the presence of strong multifractal characteristics in the gold futures market both before and after the "Americanization" reform. This signifies that the market's statistical properties cannot be described by a single scaling exponent and that fluctuations of different sizes scale differently.

Moreover, the market's memory structure also changes significantly. For small fluctuations ($q < 0$), $H(q)$ remains above 0.5 in both periods, confirming the consistent persistence of low-volatility regimes. However, a fundamental change is observed for large fluctuations ($q > 0$). Before the reform, the market exhibits anti-persistent behavior for large shocks (e.g., $H(10) < 0.5$), suggesting a tendency for corrections after major price movements. After the reform, this behavior reverses, with all $H(q)$ for $q > 0$ becoming greater than 0.5, indicating that large fluctuations are now persistent and trend-reinforcing. This fundamental change implies a significant structural reshaping of the market's response to volatility.

TABLE 3 Multifractality metrics for gold futures returns.

Period		α_{min}	α_{max}	$\triangle\alpha$	$\triangle H$	*MLM*
Pre-reform period	0.3508	0.9855	0.6347	0.4334	0.2167	
Post-reform period	0.4251	0.9706	0.5455	0.3550	0.1864	

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after.

To quantify the change in market efficiency, we analyze key metrics derived from the multifractal spectrum and the generalized Hurst exponent. The degree of multifractality, which reflects the range of scaling behaviors in a time series, is a widely used proxy for market inefficiency. A wider multifractal spectrum indicates a less efficient market, characterized by stronger long-range correlations and a greater deviation from a random walk. Specifically, we employ three primary measures, including: (1) the width of the multifractal spectrum ($\Delta\alpha$), capturing the range of scaling exponents present in the data; (2) the range of the generalized Hurst exponent (ΔH); and (3) the Magnitude of Long Memory (*MLM*) index, also known as the Market Deficiency Measure [8, 10, 29], providing a normalized value to gauge the overall level of market inefficiency. A larger value for $\Delta\alpha$, ΔH, or *MLM* signifies a higher degree of multifractality and thus lower market efficiency.

The results presented in Table 3 provide strong evidence of a significant reduction in the degree of multifractality following the "Americanization" of gold futures options. Specifically, the width of the multifractal spectrum, $\Delta\alpha$, decreases from 0.6347 in the pre-reform period to 0.5455 in the post-reform period. Similarly, the range of the generalized Hurst exponent, ΔH, experiences an even more substantial reduction, falling from 0.4334 to 0.3550. This trend is also captured by the *MLM* index, which drops from 0.2167 to 0.1864, a decrease of approximately 14%. This reduction in multifractality is visually confirmed in Figure 1, where the spectrum for the post-reform period is distinctly narrower and less left-skewed than the spectrum for the pre-reform period. These results strongly suggest that the gold futures market becomes more efficient after the "Americanization" of gold futures options.

4.2 Change in multifractal sources

To gain more insight into the efficiency change, we then analyze how the "Americanization" reform impacts the primary sources of

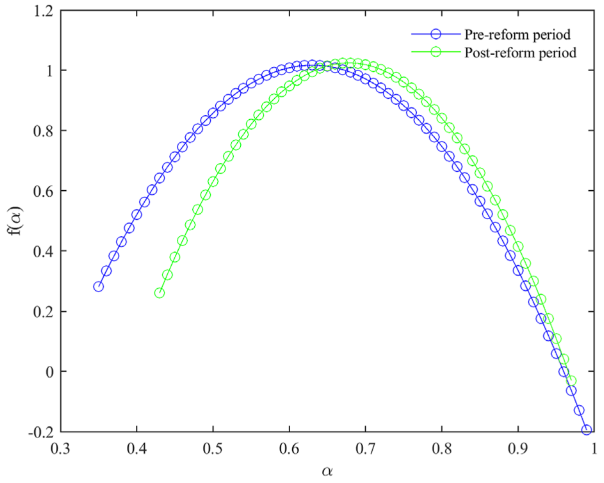

FIGURE 1
Change in multifractal spectra.

the underlying market's multifractal behavior. According to related literature [8, 15, 42, 43], the multifractality of a financial time series typically arises from two main components: (1) the fat-tailed probability distribution of returns and (2) the long-range temporal correlations inherent in the series. To disentangle the contributions of these two sources, we follow related literature [13, 24, 42, 44] and employ a standard shuffling procedure. By randomly reordering the original return series, we effectively destroy its temporal correlation structure (both linear and non-linear) while preserving its probability distribution. Consequently, any multifractality that persists in the shuffled series can be attributed solely to the influence of the fat-tailed distribution. The difference between the multifractality of the original and the shuffled series thus isolates the contribution of long-range correlations. For a more comprehensive analysis, we also include a phase-randomized surrogate series, which destroys non-linear dependencies while retaining the linear autocorrelation structure.

Table 4 presents the results of this decomposition analysis. In the pre-reform period, the multifractality metrics for the original series are only marginally higher than those for the shuffled series. For instance, the *MLM* index only decreases from 0.2167 for the original series to 0.2097 after shuffling. This indicates that long-range correlations may account for less than 5% of the total measured multifractality, suggesting a market structure where the primary source of inefficiency is the presence of extreme price movements rather than complex temporal dependencies. Therefore, market inefficiency before the reform is primarily driven by its distributional properties.

This characteristic changes significantly in the post-reform period. As shown in Table 4, the multifractality stemming from the fat-tailed distribution (as seen in the post-reform shuffled series) is substantially reduced, with its *MLM* index decreasing to 0.1152. More importantly, the relative contribution of long-range correlations to the remaining market inefficiency increases significantly. The difference between the MLM index of the post-reform original series (0.1864) and its shuffled version (0.1152) is now 0.0712. This implies that, after the reform, long-range correlations also contribute to the total observed multifractality of gold futures returns.

TABLE 4 Decomposition of the sources of multifractality.

Period	Series	α_{min}	α_{max}	$\triangle\alpha$	$\triangle H$	MLM
Pre-reform period	Original	0.3508	0.9855	0.6347	0.4334	0.2167
	Shuffled	0.3483	0.9537	0.6054	0.4194	0.2097
	Surrogated	0.4167	0.9649	0.5482	0.3510	0.1755
Post-reform period	Original	0.4251	0.9706	0.5455	0.3550	0.1864
	Shuffled	0.4597	0.8094	0.3497	0.2304	0.1152
	Surrogated	0.5444	0.7979	0.2535	0.1200	0.1393

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after. "Original", "Shuffled", and "Surrogated" denote results for the original, shuffled, and surrogated spot and futures return series.

In summary, the "Americanization" of gold futures options not only reduces the degree of market multifractality, but also fundamentally changes its structural composition. Specifically, gold futures market shifts from a state where inefficiency is primarily a consequence of its fat-tailed return distribution to a new state where, despite being more efficient overall, the remaining market inefficiency is now significantly more influenced by its complex temporal structure and long-range memory.

5 Effect of the "Americanization" reform on the price discovery function of underlying market

The previous section demonstrates that the "Americanization" of gold futures options enhances gold futures market efficiency. As futures market plays a significant role in price discovery, this section further investigates the potential effect of this reform on the market's role in price discovery by examining how it reshapes the dynamic relationship between the gold futures and spot markets.

5.1 Cross-correlation test

We first assess the overall cross-correlation between the gold futures and spot markets using the DMA coefficient ($\rho_{DMA}(s)$), which is a robust measure of the degree of co-movement between two non-stationary time series across different time scales s. It is similar to the traditional Pearson correlation coefficient but is specifically designed to handle long-range correlated data, which makes it particularly suitable for financial time series. The coefficient ranges from -1 to 1, where $\rho_{DMA}(s) = 1$ indicates perfect positive correlation, $\rho_{DMA}(s) = -1$ signifies perfect negative correlation, and $\rho_{DMA}(s) = 0$ implies no correlation at the given scale s. A higher positive value of $\rho_{DMA}(s)$ suggests a stronger tendency for the two markets to move in the same direction.

Table 5 presents the estimated DMA coefficients between gold futures and spot returns for various time scales during the pre- and

TABLE 5 DMA correlation coefficients between gold futures and spot returns.

s	4	8	16	32	64	128
Pre-reform period	0.6557	0.6531	0.6489	0.6490	0.6826	0.6227
Post-reform period	0.5288	0.5191	0.5479	0.5807	0.5676	0.5272

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after.

TABLE 6 q-order Hurst exponent for gold futures-spot cross-correlations.

q	Pre-reform period	Post-reform period
−10	0.7064	0.8216
−9	0.6955	0.8093
−8	0.6828	0.7941
−7	0.6680	0.7749
−6	0.6513	0.7503
−5	0.6329	0.7188
−4	0.6137	0.6804
−3	0.5939	0.6402
−2	0.5737	0.6072
−1	0.5528	0.5835
0	0.5313	0.5652
1	0.5096	0.5494
2	0.4887	0.5349
3	0.4695	0.5215
4	0.4523	0.5093
5	0.4372	0.4984
6	0.4241	0.4887
7	0.4128	0.4801
8	0.4030	0.4724
9	0.3944	0.4656
10	0.3870	0.4595

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after.

post-reform periods. In the pre-reform period, the futures and spot markets exhibit a strong and stable positive correlation. The DMA coefficients consistently maintain a high value of approximately 0.65 across all time scales, with the average coefficient being 0.6520. This indicates a robust and predictable linear relationship where the price movements in the two markets are tightly coupled.

After the reform, the average coefficient across all scales decreases to 0.5452, representing a substantial reduction from the pre-reform level. This weakening of the cross-correlation suggests that while the gold futures and spot markets still move together, the strength and predictability of their linear co-movement have been notably diminished after the "Americanization" of options.

5.2 Change in multifractality of gold futures-spot cross-correlations

To investigate the potential emergence of more complex, non-linear dependencies, we employ the MF-X-DMA method to analyze the scaling properties of the cross-correlation structure between gold futures and spot markets. We begin by analyzing the q-order Hurst exponent for the cross-correlation, denoted as $H_{xy}(q)$. This exponent quantifies the persistence of co-movements between the two series for market fluctuations of varying magnitudes. A dependency of $H_{xy}(q)$ on q serves as direct evidence of multifractality in the cross-correlation.

Table 6 presents the estimated $H_{xy}(q)$ for the cross-correlation between gold futures and spot return series across both the pre- and post-reform periods. The strong dependence of $H_{xy}(q)$ on q in both periods implies that the interaction between the gold futures and spot markets is inherently multifractal. Therefore, a single linear correlation coefficient may not be sufficient to fully characterize their relationship, as the nature of their co-movement is contingent on the size of market fluctuations.

In addition, there is a significant change in the persistence characteristics of the cross-market dynamics. For co-movements associated with small fluctuations ($q < 0$), $H_{xy}(q)$ is consistently greater than 0.5 in both periods, indicating a persistent or trend-reinforcing relationship during low-volatility regimes. This persistence appears to intensify in the post-reform period, as evidenced by the general increase in $H_{xy}(q)$ values for negative q. A more fundamental transformation, however, is observed in the dynamics of large fluctuations ($q > 0$). Before the reform, the cross-correlation for large shocks is characterized by anti-persistence for $q \geq 2$ (e.g., $H_{xy}(10) = 0.3870$), suggesting that strong co-movements are typically followed by a decoupling or a corrective reversal. Notably, this anti-persistent property of large-scale co-movements is no longer observed after the reform. In the post-reform period, the $H_{xy}(q)$ values for nearly all positive q are above the 0.5 threshold, indicating a decisive shift to a persistent cross-correlation structure. This change suggests that after the "Americanization" of gold futures options, major information events now tend to trigger stronger and more sustained synchronized responses across both markets.

This change towards a more complex interaction is quantitatively confirmed by the measures of the degree of cross-market multifractality, presented in Table 7. These metrics, consistent with those employed in Section 4, provide a direct assessment of the complexity of the dynamic relationship between the two markets. A higher value for these indices points to a more intricate, non-linear, and time-varying correlation structure.

TABLE 7 Multifractality metrics for gold futures-spot cross-correlations.

Period		α_{min}	α_{max}	$\triangle\alpha$	$\triangle H$	*MLM*
Pre-reform period	0.3127	0.8151	0.5024	0.3194	0.1597	
Post-reform period	0.3984	0.9446	0.5462	0.3621	0.1810	

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after.

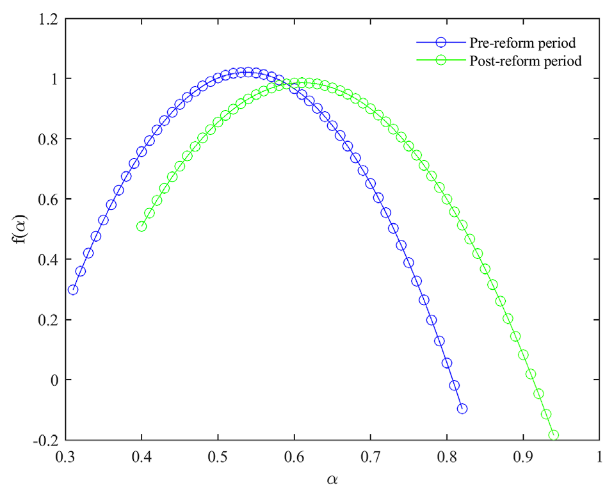

FIGURE 2
Change in Multifractal spectra for gold futures-spot cross-correlations.

Table 7 reveals a clear and consistent increase in the degree of cross-market multifractality after the reform. The width of the cross-multifractal spectrum ($\Delta\alpha$) increases from 0.5024 to 0.5462, while the range of the generalized Hurst exponent (ΔH) rises from 0.3194 to 0.3621. The cross-market MLM index (*MLM*) further illustrates this trend, experiencing a notable increase of over 13% from 0.1597 to 0.1810. This broadening of the multifractal spectrum is also visually depicted in Figure 2.

Collectively, our findings indicate that while the linear correlation between the gold futures and spot markets weakens after the reform, their relationship becomes significantly more complex and multifractal. These results suggest that the increased flexibility of American-style options may encourage more sophisticated trading and hedging strategies, whose effects are not fully captured by linear measures but are evident in a nonlinear dependency.

5.3 Sources of multifractality of gold futures-spot cross-correlations

Having established that the cross-correlation between the futures and spot markets has become significantly more multifractal, we then decompose the sources of this complexity. Specifically, multifractality in a cross-correlation can arise from either the distributional properties of the individual series (i.e., their fat tails) or from the intricate, non-linear coupling and long-range memory that exist between the two series. To distinguish between these sources, we adopt the same procedure used in Section 4. By applying a common random shuffling order to both the futures and spot return series simultaneously, we destroy their respective temporal structures and the cross-correlations between them, while preserving the individual distributional properties. Therefore, any remaining cross-market multifractality in the shuffled pair is attributable to the fat tails of the underlying distributions, while the difference reveals the contribution from their genuine temporal and non-linear inter-linkages.

TABLE 8 Change in sources of multifractality for spot-futures cross-correlations.

Period	Series	α_{min}	α_{max}	$\triangle\alpha$	$\triangle H$	*MLM*
Pre-reform period	Original	0.3127	0.8151	0.5024	0.3194	0.1597
	Shuffled	0.3677	0.7912	0.4234	0.2517	0.1259
	Surrogated	0.3680	0.6557	0.2877	0.1540	0.0770
Post-reform period	Original	0.3984	0.9446	0.5462	0.3621	0.1810
	Shuffled	0.4390	0.7787	0.3398	0.2148	0.1074
	Surrogated	0.5111	0.8483	0.3371	0.2035	0.1315

"Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after. "Original", "Shuffled", and "Surrogated" denote results for the original, shuffled, and surrogated spot and futures return series.

Table 8 presents the decomposition results for the cross-market multifractality metrics. As shown, in both the pre- and post-reform periods, the multifractality metrics for the original series pair are consistently higher than those for the shuffled and surrogated pairs. For instance, the original values of MLM are substantially larger than their shuffled counterparts. This result indicates that both the distributional properties and the cross-market temporal correlations are important sources of the observed multifractality.

Notably, there is a significant shift in this composition after the reform. The difference in any metric between the original series and the shuffled pair becomes larger, indicating that the contribution from genuine cross-market correlations is strengthened. This finding suggests a more deeply integrated and sophisticated price discovery process, where the non-linear coupling between the markets has become a much more dominant driver of their dynamic interaction.

5.4 Change in nonlinear granger causality

In the previous sections, we show that the futures-spot relationship becomes a more complex and non-linear system. This section investigates how this transformation may affect the causal information flow between the two markets. Price discovery primarily focuses on identifying which market leads in incorporating new information. Following related literature [8, 23, 25, 45], we utilize the non-linear Granger causality test to examine

TABLE 9 Change in Non-linear Granger causality between spot and futures returns.

Lag	Pre-reform period		Post-reform period	
	Spot ↛ futures	futures ↛ spot	Spot ↛ futures	futures ↛ spot
1	0.1606	2.0519***	−0.4484	−1.7847
2	1.1374	2.8149***	−1.2672	−1.6739
3	0.7626	2.3287***	−1.1350	−1.7285
4	0.7889	1.9131**	−0.7115	−1.7548

"spot ↛ futures" denotes the null hypothesis that spot returns do not nonlinearly Granger cause futures returns, while "futures ↛ spot" denotes the null hypothesis that futures returns do not nonlinearly Granger cause spot returns. "Pre-reform period" is the sub-period before the "Americanization" reform, and "Post-reform period" refers to the sub-period after. "*," "**," and "***" suggest rejection of the null hypothesis at the 10%, 5%, and 1% significance levels, respectively.

the direction and significance of predictive power. This test is crucial as it can detect non-linear causal linkages that would be missed by traditional linear tests, making it highly suitable for the complex market environment.

Table 9 presents the results of the non-linear Granger causality tests for lags ranging from 1 to 4. We test two null hypotheses: "H_0: Spot returns do not non-linearly Granger-cause futures returns (Spot ↛ Futures)", and "H_0: Futures returns do not non-linearly Granger-cause spot returns (Futures ↛ Spot)". Rejection of the null hypothesis implies a significant causal information flow from one market to the other.

As shown in Table 9, in the pre-reform period, there is a unidirectional information flow from the futures market to the spot market. For all tested lags, the null hypothesis that futures do not Granger-cause spot is strongly rejected at high significance levels. In contrast, we find no evidence of a causal link from the spot market to the futures market. This classic lead-lag relationship establishes the futures market as the primary center for price discovery before the reform.

Notably, this causal relationship completely disappears in the post-reform period. Across all lags, for both directions, we can no longer reject the null hypothesis of no Granger causality. However, this disappearance of a detectable lead-lag relationship does not suggest a failure of the price discovery function. On the contrary, viewed in conjunction with our earlier findings on improved market efficiency, it suggests a natural progression in the market's development. Specifically, the "Americanization" of gold futures options, by fostering a more deeply integrated and sophisticated trading environment, may accelerate the speed of information transmission between the markets to the point where it becomes nearly instantaneous. The price discovery process has transitioned from a sequential, leader-follower model to a synchronized model, where new information is impounded into the prices of both markets almost simultaneously. This indicates the development of a more efficient market, with the predictive lead previously held by the futures market now being part of a contemporaneously linked system.

6 Conclusion and discussion

This paper investigates how the "Americanization" of gold futures options, a significant financial liberalization reform on the Shanghai Futures Exchange, affects the underlying market dynamics of gold futures. By employing a multifractal and non-linear causality framework, we uncover a multi-faceted transformation that extends from the market's internal efficiency to its external price discovery function.

Our analysis yields three interconnected findings. First, the reform enhances the efficiency of the gold futures market (i.e., the underlying asset of the options affected), as evidenced by a significant reduction in its degree of multifractality. Second, this improvement in efficiency is accompanied by a fundamental reshaping of the futures-spot relationship: specifically, while the simple linear correlation between the two markets weakens, their interaction evolves into a more complex, non-linear, and multifractal system. Finally, non-linear Granger causality test shows that the futures market no longer holds a unidirectional lead over the spot market post-reform. Taken together, our findings suggest that the reform, by fostering a more deeply integrated and sophisticated trading environment, accelerates the speed of information transmission to the point of near-instantaneousness. The price discovery process transitions from a traditional leader-follower model to a synchronized one, where new information is incorporated into both markets almost simultaneously.

Our study offers several implications. For policymakers and regulators, our results suggest that institutional reforms aimed at increasing product flexibility can successfully enhance market efficiency but may also lead to more intricate inter-market dependencies that require more sophisticated monitoring. For market participants, the shift to a synchronized pricing model implies that arbitrage opportunities based on simple lead-lag strategies are likely to diminish in more mature markets.

This paper also has some limitations that open avenues for future research. First, our study focuses exclusively on the Chinese gold market. While this provides a clean natural experiment, the findings may not be generalizable to other asset classes or to markets with different regulatory environments and participant structures. Second, while the reform represents a major structural break, we cannot entirely rule out the influence of other confounding macroeconomic factors that may have occurred during our sample periods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. Requests to access these datasets should be directed to Dayong Lv, dylv@lixin.edu.cn.

Author contributions

LF: Conceptualization, Formal Analysis, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. ZF: Data curation, Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review and editing. MY: Data curation, Methodology, Validation, Writing – review and editing. DL: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Validation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Jin X, Zhao J, Luo X. Why are the prices of european-style derivatives greater than the prices of american-style derivatives? *J Futures Markets* (2022) 42:1772–93. doi:10.1002/fut.22322

2. Lu L, Xu W, Qian Z. Efficient willow tree method for european-style and american-style moving average barrier options pricing. *Quant Finance* (2017) 17:889–906. doi:10.1080/14697688.2016.1231416

3. D'Amico G, Janssen J, Manca R. European and American options: the semi- Markov case. *Physica A: Stat Mech Its Appl* (2009) 388:3181–94. doi:10.1016/j.physa.2009.04.016

4. Levendorskiĭ S. American and European options in multi-factor jump-diffusion models, near expiry. *Finance Stochastics* (2008) 12:541–60. doi:10.1007/s00780-008-0070-z

5. Kojić M, Mitić P, Antunes DE Araujo FH. Multiscale nonlinearity in energy commodities and bond markets: MFDCCA via MODWT and granger causality. *Fractals* (2025) 33(0):2550030. doi:10.1142/s0218348x25500306

6. Zhou W, Huang J, Wang M. Multifractal characteristics and information flow analysis of stock markets based on multifractal detrended cross-correlation analysis and transfer entropy. *Fractal and Fractional* (2025) 9:14. doi:10.3390/fractalfract9010014

7. Acikgoz T. *The multifractal nature of cross-correlations between emerging market equities and financial assets: an econophysics perspective*. Computational Econ (2025). doi:10.1007/s10614-025-10991-4

8. Lv D, Zhou Y, Zhang J, Yin L. Unintended consequences of quote limits policy on stock market dynamics: evidence from the MF-X-DMA analysis. *Front Phys* (2025) 13:1642788. doi:10.3389/fphy.2025.1642788

9. Wang J, Xu H, Ge S, Jiang W, Yan Y, Shao W. The multifractal phenomenon of stock price caused by "Tesla Rights Defense Event". *Fluctuation Noise Lett* (2024) 23:2450048. doi:10.1142/s0219477524500482

10. Ruan Q, Hu S, Zhang J, Chu X, Lv D. Relaxing daily price limits and stock market cross-correlation: evidence from MF-X-DMA analysis. *Fluctuation Noise Lett* (2023) 22:2350042. doi:10.1142/s0219477523500426

11. Lee M-J, Choi S-Y. Comparing market efficiency in developed, emerging, and frontier equity markets: a multifractal detrended fluctuation analysis. *Fractal and Fractional* (2023) 7:478. doi:10.3390/fractalfract7060478

12. Jiang Z-Q, Xie W-J, Zhou W-X, Sornette D. Multifractal analysis of financial markets: a review. *Rep Prog Phys* (2019) 82:125901. doi:10.1088/1361-6633/ab42fb

13. Zhao R, Dai P-F. A multifractal cross-correlation analysis of economic policy uncertainty: evidence from China and US. *Fluctuation Noise Lett* (2021) 20:2150041. doi:10.1142/s0219477521500413

14. Peng CK, Buldyrev SV, Havlin S, Simons M, Stanley HE, Goldberger AL. Mosaic organization of DNA nucleotides. *Phys Rev E* (1994) 49:1685–1689. doi:10.1103/physreve.49.1685

15. Kantelhardt JW, Zschiegner SA, Koscielny-Bunde E, Havlin S, Bunde A, Stanley HE. Multifractal detrended fluctuation analysis of nonstationary time series. *Physica A: Stat Mech Its Appl* (2002) 316:87–114. doi:10.1016/s0378-4371(02)01383-3

16. Podobnik B, Stanley HE. Detrended cross-correlation analysis: a new method for analyzing two nonstationary time series. *Phys Rev Lett* (2008) 100:084102. doi:10.1103/physrevlett.100.084102

17. Zhou W-X. Multifractal detrended cross-correlation analysis for two nonstationary signals. *Phys Rev E* (2008) 77:066211. doi:10.1103/physreve.77.066211

18. Jiang Z-Q, Zhou W-X. Multifractal detrending moving-average cross-correlation analysis. *Phys Rev E* (2011) 84:016106. doi:10.1103/physreve.84.016106

19. Shao Y-H, Gao X-L, Yang Y-H, Zhou W-X. Joint multifractality in cross-correlations between grains and oilseeds indices and external uncertainties. *Financial Innovation* (2025) 11:21. doi:10.1186/s40854-024-00669-5

20. Li H, Lou F, Wang Q, Li G. Interpretable graph clustering on massive attribute networks via multi-agent dynamic game. *Chaos, Solitons & Fractals* (2025) 199:116654. doi:10.1016/j.chaos.2025.116654

21. Li J, Lu X, Qu L. Effectiveness of the RMB exchange rate regime reform: a new perspective from MF-DMA and MF-X-DMA. *Physica A: Stat Mech Its Appl* (2019) 531:121535. doi:10.1016/j.physa.2019.121535

22. Lu X, Tian J, Zhou Y, Li Z. Multifractal detrended fluctuation analysis of the Chinese stock index futures market. *Physica A: Stat Mech Its Appl* (2013) 392:1452–1458. doi:10.1016/j.physa.2012.11.037

23. Vogl M, Kojić M. Green cryptocurrencies versus sustainable investments dynamics: exploration of multifractal multiscale analysis, multifractal detrended cross-correlations and nonlinear granger causality. *Physica A: Stat Mech Its Appl* (2024) 653:130085. doi:10.1016/j.physa.2024.130085

24. Ye S, Dai P-F, Nguyen HT, Huynh NQA. Is the cross-correlation of EU carbon market price with policy uncertainty really being? A multiscale multifractal perspective. *J Environ Manage* (2021) 298:113490. doi:10.1016/j.jenvman.2021.113490

25. Zhou Y, Lu B, Lv D, Ruan Q. The informativeness of options-trading activities: non-linear analysis based on MF-DCCA and granger test. *Physica A: Stat Mech Its Appl* (2019) 534:122269. doi:10.1016/j.physa.2019.122269

26. Baek E, Brock W. *A general test for nonlinear granger causality: bivariate model*. Iowa State University and University of Wisconsin at Madison Working Paper (1992).

27. Li H, Lou F, Wang Q, Li G, Perc M. Multiresolution clustering on massive attributed graphs by means of optimal aggregated markov chains. *IEEE Trans Netw Sci Eng* (2025) 13:1–16. doi:10.1109/tnse.2025.3579427

28. Ruan Q, Wang Z, Liu J, Lv D. Is foreign capital smarter? Multifractal evidence from the shanghai–hong kong stock connect program. *Fluctuation Noise Lett* (2020) 19:2050047. doi:10.1142/s0219477520500479

29. Ock SE, Lee M, Song JW. Multifractal analysis of the impact of fuel cell introduction in the Korean electricity market. *Fractal and Fractional* (2024) 8. doi:10.3390/fractalfract8100573

30. Khuntia S, Pattanayak JK. Adaptive long memory in volatility of intra-day bitcoin returns and the impact of trading volume. *Finance Res Lett* (2020) 32:101077. doi:10.1016/j.frl.2018.12.025

31. Zhang P, Yin S, Sha Y. Global systemic risk dynamic network connectedness during the COVID-19: evidence from nonlinear granger causality. *J Int Finan Markets, Inst Money* (2023) 85:101783. doi:10.1016/j.intfin.2023.101783

32. Shao S, Stoumbos R, Zhang XF. The power of firm fundamental information in explaining stock returns. *Rev Acc Stud* (2021) 26:1249–1289. doi:10.1007/s11142-020-09572-7

33. Ma C, Xiao R, Mi X. Measuring the dynamic lead–lag relationship between the cash market and stock index futures market. *Finance Res Lett* (2022) 47:102940. doi:10.1016/j.frl.2022.102940

34. Liu P-T, Cao X-B, Wang H-Y. Multifractal analysis of Chinese industry and stock markets fluctuation under the COVID-19 pandemic. *Fluctuation Noise Lett* (2023) 23:2450013. doi:10.1142/s0219477524500135

35. Xie W, An Y. Should dominant contracts move to nearby months? Evidence from Chinese agricultural futures markets. *Appl. Econ.* (2023) 55:4817–4840. doi:10.1080/00036846.2022.2131718

36. Lin C-B, Chou RK, Wang GHK. Investor sentiment and price discovery: evidence from the pricing dynamics between the futures and spot markets. *J Banking & Finance* (2018) 90:17–31. doi:10.1016/j.jbankfin.2018.02.014

37. Xie W, An Y. Information flow across the futures term structure: evidence from Chinese corn futures market. *J Futures Markets* (2025) 45:896–916. doi:10.1002/fut.22595

38. Bianchi ML, Tassinari GL, Fabozzi FJ. Fat and heavy tails in asset management. *J Portfol Manage* (2023) 49:236–263. doi:10.3905/jpm.2023.1.501

39. Lin W, Taamouti A. Portfolio selection under non-gaussianity and systemic risk: a machine learning based forecasting approach. *Int J Forecast* (2024) 40:1179–1188. doi:10.1016/j.ijforecast.2023.10.007

40. Li H-J, Gao J, Wang Q, Qiu C, Li G. Generalized cluster formation game for explainable attributed graph clustering. *Chaos, Solitons & Fractals* (2025) 200:116947. doi:10.1016/j.chaos.2025.116947

41. Ma H, Prosperino D, Haluszczynski A, Räth C. Linear and nonlinear causality in financial markets. *Chaos: An Interdiscip J Nonlinear Sci* (2024) 34. doi:10.1063/5.0184267

42. Drożdż S, Kwapień J, Oświecimka P, Rak R. Quantitative features of multifractal subtleties in time series. *Europhysics Lett* (2009) 88:60003. doi:10.1209/0295-5075/88/60003

43. Kwapień J, Blasiak P, Drożdż S, Oświęcimka P. Genuine multifractality in time series is due to temporal correlations. *Phys Rev E* (2023) 107:034139. doi:10.1103/physreve.107.034139

44. Rak R, Grech D. Quantitative approach to multifractality induced by correlations and broad distribution of data. *Physica A: Stat Mech Its Appl* (2018) 508:48–66. doi:10.1016/j.physa.2018.05.059

45. Diks C, Wolski M. Nonlinear granger causality: guidelines for multivariate analysis. *J Appl Econom* (2016) 31:1333–1351. doi:10.1002/jae.2495