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Analysis of major properties of metal prices using new methods: Structural breaks, non-linearity, stationarity and bubbles

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ABSTRACT

This study investigates major properties of prices of metals (gold, silver, platinum, palladium and copper) such as structural breaks, non-linearity, stationarity, and bubble incidences during 1990–2021 For robustness of results, both daily and weekly data sets were used, while two conventional unit root tests and two recent stationarity tests (including a new one) that account for structural breaks and non-linearity were also employed. The recently introduced method of identifying and detecting price bubble was also used. Preliminary tests show that prices of the metals exhibit structural breaks and non-linearity during the study period. The traditional unit root tests reveal that prices of all the metals are not stationary I(1). The application of two unit root tests, that account for structural breaks and non-linearity, produced stationary results I(0) for the metals' prices in all the periods. However, the result of new method is more robust than the earlier one especially when weekly data is considered alongside daily data for Platinum and Silver. Some incidences of price bubbles were also detected in the metal market during the period. A number of policy recommendations deduced from the empirical results are well discussed in the concluding part of the paper.

1. Introduction

It has been stated in the literature that a good knowledge of the time-series features of commodity prices is a precondition to practical examination of efficiency, risk management and forecasting issues (Wang and Tomek, 2007). Analysis of the time series characteristics of product prices in order to draw efficiency implications is typically anchored on the efficient market hypothesis (EMH) originated by Fama (1965 & 1970) and tested for diverse assets and commodities. This hypothesis shows that information efficiency is very important because no investor would reap unusual returns as a result of any information advantage over the others (Bayraktar, 2012; Arouri et al., 2013; Adewuyi et al., 2020). This means that, if the prices of assets wholly capture the existing market information, there would not be differentiated returns among the investors. It also implies that future price changes would reflect future news and would have nothing to do with currents price changes (Arouri et al., 2013; Zhang et al., 2014; Adewuyi et al., 2020).

Further, random walk properties of commodity prices influence the trading strategies adopted by investors. Trading strategies differs between when returns feature random walks (positive autocorrelation or persistence) over short horizons and when they show negative autocorrelation (mean reversion) over long horizons. Thus, as the investment horizon reduces (enlarges), an investor would invest less (more) in assets when the comparative risk aversion is less (greater) than unity, rather than when the returns were serially independent (Wang and Tomek, 2007; Worthington and Higgs, 2003). In the case where the market follows a random walk, it means commodities are being correctly priced at an equilibrium level, while lack of a random walk suggests twists in the capital and risk pricing which has significant implications for financial resource allocation and economic development.[1] Forward market agents (Arbitrageurs and speculators) enthusiastically trail the trend of prices of metals and other commodities in cross-market futures trading since they mirror certain quality that attracts arbitrage (Narayan and Liu, 2011; Adewuyi et al., 2020). Similarly, policymakers in commodity-reliant economies are interested in the knowledge of the trend of commodity prices for managing risk associated with export income volatility arising from instability in commodity prices.

Stationarity is linked with market efficiency in the sense that, if market prices are not mean reverting or non-stationary it implies that shocks to the markets (or prices) are permanent and market returns

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[1] https://core.ac.uk/download/pdf/143883406.pdf.

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exhibit non-predictability, hence, the market is efficient (Bouri et al., 2017). Efficiency of the commodity markets may be influenced by structural changes (breaks) and non-linear adjustment in which prices are not directly proportional to measure of quantity demand. Structural market change prevails when there is a shift in the fundamental functioning of a market due to some factors including uncertainty associated with financial policies and reserves accumulation of major Central Banks, changes in global production and consumption, instability in European Union, Trade war and Banking sector instability as well as global economic or financial or health crises.[2] Similarly, there are occurrence of nonlinear market price adjustment as a result of market frictions, transaction costs (bid-ask spread, short selling, and borrowing constraints), heterogeneous agents' interactions and beliefs (Hasanov and Omay, 2007). All these features of commodity markets and prices are to be recognized by market operators and analysts in the examination of price behaviour or properties. Thus, accounting for structural breaks and non-linearity may make prices reflect stationary (mean reverting) behaviour and hence, market becomes inefficient.

Another major factor influencing efficiency of commodity market is the occurrence of bubbles in products' prices (Bouri et al., 2017; and Phillips and Shi, 2018). The deviation of price of an asset or commodity from its intrinsic or fundamental value connotes that the asset or commodity market exhibits price bubbles. When the original asset price rises unexpectedly in a specific period and then slumps tragically, a price bubble has occurred (Lind, 2009; Khan & Köseoğlu, 2020). The need to analyse the bubbles phenomena is informed by the fact that some crises (the dot-com bubble in 2001, the house price bubble and mortgage crises in 2008) in the past were traceable to the burst of the price bubbles (Khan and Köseoğlu, 2020). Thus, in order to avert major crisis there is need to monitor and detect bubbles occurrence early enough.

Following the slowdown of global production and consumption of commodities and the interruption of information and transportation flows as well as government interventions during COVID-19 pandemic, there is likely to be structural changes or bubbles in the prices of metals. It is therefore important to examine whether the diverse distortions (structural changes, non-linear price adjustment and bubbles) which constitute shocks to metal prices have temporary or permanent effect so as to guide the decisions of the economic agents.

The contribution of this paper to the existing studies is anchored on the following gaps. First, almost all the previous studies reviewed in this work considered only structural break, overlooking the issue of non-linearity in the structure of metal price. Apart from this, their findings are mixed and inconclusive, implying the need for more studies. Second, even though one of the studies reviewed (Adewuyi et al., 2020) used unit root test that involves both structural break and non-linearity developed by Christopoulos and Leon-Ledesma (2010), this test is based on KSS non-linear unit root test which has been criticized in the literature (Kruse, 2011).[3] However, Kruse (2011) proposed a more flexible approach using modified ESTAR model.[4] Very recently, Güriş (2018) follows Kruse approach in modeling non-linear adjustment (via modified ESTAR model) while structural breaks are modeled through a Fourier function. It is therefore imperative to apply this new method to test the stationarity property of metals so as to obtain a set of more robust results for policy analysis and decision making. Its flexibility in capturing structural breaks makes it suitable for application to price movement during both turbulent and stable periods. Third, none of the previous studies simultaneously considered testing stationarity of prices of many metals accounting for structural breaks and non-linearity, and also covered identification of bubbles in a single study. This is the first study to apply the newly developed bubble monitoring and detecting technique proposed by Phillips and Shi (2018) to metal market covering prices of a range of products. Addressing this shortcoming of the previous studies enables this current study to provide robust findings on major issues affecting the decisions of the metal market's stakeholders. These are the gaps in the existing studies address by this current study. Thus, the main objective of this study is to assess the major properties of metal market in terms of convergence status of prices of five metals in the context of structural breaks and non-linearity. It also attempts to identify and analyse bubble incidences in the market.

After the foregoing introduction section is section 2 which covers review of literature and section 3 which focuses on the methodology of the study. Section 4 presents the empirical results with discussion, while section 5 summarises and concludes the paper with policy recommendations.

2. Review of literature

The literature on the properties of prices of metals includes those on bubbles, long-memory/persistence and stationarity. Available articles are examined in the following paragraphs.

Starting with studies that focus on long-memory/persistent and stationarity of prices of metals, Cheung and Lai (1993) employed modified Re–Scaled (RIS) method to discover long memory **be**haviour in gold returns which is irregular during 1973–1987. Likewise Figuerola-Ferretti and Gilbert (2008) using standard methods of fractional integration and cointegration and reported that the commodity prices reflect similar fractional integration degree but no evidence of fractional cointegration. Similarly, Shafiee and Topal (2010) used long–term trend reverting jump and dip diffusion model to assess gold price trend during 1968–2008. They discovered that long–term dips and jumps characterized gold price trend. They also found that gold price tends to slip back to its long–term trend after a jump. In the same vein, Narayan and Liu (2011) adopted two recently developed unit root tests (that permit two structural breaks in the series) to look into the characteristics of shocks to prices of some metals in the period January 1976 to March 2010.[5] On the basis of the Narayan and Popp (2010) test, the unit root null hypothesis was not accepted for iron ore and tin. Further, with the aid of the unit root test of Liu and Narayan (2010),.the null hypothesis was not accepted for iron ore, nickel, zinc, lead, and tin. The results suggest that shocks to prices of gold, silver, platinum, aluminum, and copper are not transitory.

Other studies include Arouri et al. (2012) which employed different approaches to evaluate four precious metals.[6] Analysing data from January 4, 1999 to March 31, 2011 with the methods, they found evidence of long–memory in spot and futures prices of the metals considered. Spot and futures prices of the metals demonstrate structural changes which are connected with the 2008/2009 global financial crisis. They also revealed that, although crumble gradually, metals' volatility and returns persist. Using similar methods, Uludag and Lkhamazhapov (2014) analysed the long–memory properties and structural changes in returns and volatility of both spot and futures gold prices during 2008M06D27 to 2013M05D31. With both GPH and mGPH tests, they divulged evidence of long–memory patterns for only spot and futures gold volatility. However, using GSP test they reported that long–memory behaviour features in both spot and futures gold returns and volatility. In addition, utilising Bai and Perron (1998, 2003) test, they ascertained that spot and futures prices of gold exhibit structural changes.

Also, Gil-Alana and Tripathy (2014) applied different approaches to

[2] https://www.nap.edu/read/10211/chapter/7.

[3] KSS has been criticied to be based on ESTAR with location parameter in the smooth transition function equal to zero: ESTAR means: Exponential Smooth Transition Autoregressive.

[4] ESTAR model was modified with a non-zero location parameter.

[5] Narayan and Popp, 2010-NP test; and Liu and Narayan et al., 2010-LN test.

[6] Geweke and Porter–Hudak (GPH), Gaussian Semi-parametric (GSP), Exact Maximum Likelihood (EML), modified Iterative Cumulative Sum of Square (ICSS) and ARFIMA–FIGARCH methods.

discover volatility persistence and leverage effect in six non-ferrous metals in India (copper, lead, nickel, zinc, tin and aluminum spot and futures series) across 1st January 2009 to 30th June 2012. Further, the model revealed asymmetric effect in seven out of the twelve non-ferrous metals spot and futures series, while the leverage effect was indicated in ten series. The returns series were seen to be non-stationary while the squared returns series displays long memory. In a related study, Gil–Alana et al. (2015) assessed the properties of prices of 5 principal precious metals (gold, silver, rhodium, palladium and platinum) with fractional integration methods controlled for structural break in the period of 1972:1 to 2013:12. Except palladium, they found other precious metals showcasing structural breaks, which when considered enabled the precious metals to show high level of persistence. Using a combination of conventional and new unit root tests, Adewuyi et al. (2020) analysed the time series feature of prices of 4 precious metals (gold, palladium, platinum and silver) and 7 industrial metals (aluminum, copper, lead, nickel, steel, tin, and zinc) with monthly and quarterly data covering 1960–2017. They indicated that, controlling for both structural break and non-linearity, the prices of all the metals are stationary.

Another study by Tapia et al. (2020) used Entropy techniques to evaluate dynamic behaviour of copper price between 1900 and 2015. Results reveal that copper prices do not exhibit periodical behaviour but chaotic one. Also, results show that copper price follow patterns that are difficult to be generated by stochastic process such as nonlinearity, non-Gaussian, and dynamic deterministic trend. Moreover, Yıldırım et al. (2020) analyses the return and volatility spillover effect between prices of oil and precious metals using the dynamic causality approach with daily data covering the period from 1990 to 2019. Using mean and variance causality methods, there is causality running from the oil return to precious metal return. After 2000s, there is strong volatility spillover effect from the oil market to the precious metal markets. They noticed that structural changes (breaks) influence the causality results.

Efficiency of metals' markets has been anlysed by some studies. For example, Kenourgios and Samitas (2004) assess the applicability of efficient market hypothesis for copper futures contract traded on the London Metal Exchange during 1990s. They utilised cointegration and error correction model to test for both long-run and short-run efficiency. They reported that the copper market is inefficient. Also, Otto (2010) investigates the validity of the weak-form market efficiency hypothesis for six industrial metals (Copper, Aluminum, Zinc, Nickel, Tin and Lead) traded at the London Metal Exchange.during post-Tin crisis period (1989–2007). He employed Box & Pierce Q-statistics and diverse variance ratio tests which reject the random-walk hypothesis for only lead. In a related study, Ntim et al. (2015) examine whether (or not) the weak-form efficiency hypothesis hold for the global gold markets using the conventional parametric variance-ratio tests and their non-parametric modifications with daily spot price of 28 emerging and developed markets during 1968–2014. They found that the likelihood of not accepting the weak-form efficiency hypothesis is less in developed gold markets than in emerging ones.[7]

In the same vein, Charles et al. (2015) analyses the applicability of weak-form efficiency to gold, silver and platinum.markets employing the automatic portmanteau and variance ratio tests with daily closing spot prices from January 1977 to October 2013. They discovered dynamism in the predictability of return of these markets based on the current economic and political circumstances. They indicated that the level of the weak-form efficiency of gold and silver markets has been recovering steadily. They stated that, among the three precious metals' markets considered, the gold market has been very efficient. Also, Mensi et al. (2020) investigate the effect of COVID-19 crisis on the multifractality of gold and oil prices during April 23, 2018 to April 24, 2020. They employed the Asymmetric Multifractal Detrended Fluctuation Analysis (A-MF-DFA) method to study 15-min interval intraday data. The results show that, prior to the outbreak, the gold market was more inefficient during downward trends, while results changed during the outbreak such that gold is more inefficient during upward trends. The investors' sentiment effect is underscored by the sensitivity of the efficiency of gold and oil markets to scales, market trends, and the COVID-19 outbreak.

Studies have also cover issue of price bubbles, such that Lucey and O'Connor (2013) examined this phenomenon in the gold spot price during 1989:M07 to 2013:M07 using ADF tests for rational speculative bubbles and Markov Switching Augmented Dickey-Fuller (MSADF) tests for seasonally bursting bubbles. The study revealed that, with variance switching between regimes there is no evidence of bubble, (but gold and its lease rate are related), while with constancy of variance in gold prices rational speculative bubbles show-up, suggesting that gold prices are essentially a function of its lease rates. Similarly, Harvey et al. (2014) employed a bubble detection method developed Phillip et al. (2011: PWY test) to disclose moderate indication of speculative bubbles in spot prices of gold, crude oil, silver and platinum and 3-months futures prices of aluminum and copper. In the same vein, Zhao et al. (2015) deployed a blend of SADF and GSADF tests to explore the phenomenon of bubbles in gold during 1973:M01 to 2014:M03.[8] The study uncovered the fact that gold prices display explosive bubbles in the financial crisis period as a lot of investors considered gold as a safe haven and a hedge.

Likewise, Su et al. (2017) utilised GSADF test to reveal if bubbles crop-up in iron ore price during 1980M01 to 2016M12. They pointed out that bubbles manifested in 4 different episodes, especially when price volatility is likely to occur. Also, Su et al. (2020) employed the same approach to see whether multiple bubbles occurred in the copper price during 1980–2019. They found that the bubbles in copper prices are driven by speculation, variation in the U.S. dollar index, copper supply and demand, and interest rate. In a related study, Khan & Köseoğlu (2020) assessed the occurrence of multiple bubbles in palladium prices from January 1994 to January 2020 using the GSADF test. Empirical findings reveal occurrence of four bubbles episodes: 1997–1998, 1999–2001, 2011 and 2019–2020. Also, Gharib et al. (2020) investigated the incidence of bubbles contagion in the WTI and gold prices during COVID-19 pandemic using the modified GSADF test and time-varying Granger causality approaches. They found that common bubbles exist in the WTI oil and gold markets in March 2020 and April 2020. They also discovered that, during this period, there was a bilateral contagion effect of bubbles in both markets.

The foregoing has shown that studies on examination of the stationarity of prices of metals have used diverse methods for analysis with inconclusive findings. Almost all the studies reviewed considered only structural break, overlooking the issue of non-linearity in the structure of metal prices. Even though one of the studies reviewed (Adewuyi et al., 2020) used unit root test that involves both structural break and non-linearity developed by Christopoulos and Leon-Ledesma (2010), this test is based on KSS non-linear unit root test which has been crriticised to be based on ESTAR model with location parameter in the smooth transition function equal to zero (Kruse, 2011).[9] However, Kruse (2011) proposed a more flexible approach using ESTAR with a non-zero location parameter. Very recently, Güriş (2018) follows Kruse approach in modeling non-linear adjustment (via ESTAR model) while structural breaks are modeled through a Fourier function It is therefore imperative

[7] They revealed that gold markets in Egypt, Indonesia, Mexico, Nepal, Pakistan, Russia, Saudi Arabia, UAE and Vietnam exhibit weak-form inefficiency, while gold markets in Hong Kong, Japan, Switzerland, UK and US are weak form efficient. They also reported mixed results for gold markets in Australia, Bahrain, Brazil, Canada, China, Germany, India, Malaysia, Singapore, South Africa, South Korea, Taiwan, Thailand and Turkey.

[8] Sup Augmented Dickey Fuller (SADF) and Generalized Sup ADF (GSADF) introduced by Phillips et al. (2011a, 2012 and 2013).

[9] ESTAR means: Exponential Smooth Transition Autoregressive.

to apply this new method to test the stationarity property of metals so as to obtain a set of more robust results for policy analysis. Beside, its flexibility in capturing structural breaks makes it suitable for application to price movement during both turbulent and stable periods. Further, none of the previous studies simultaneously considered testing stationarity of prices of many metals accounting for structural breaks and non-linearity, and also covered identification of bubbles in a single study. Moreover, none of the earlier studies applied the newly developed bubble monitoring and detecting technique proposed by Phillips and Shi (2018) to metal market covering prices of a range of products. Addressing this shortcoming of the previous studies enables this current study to provide robust findings on major issues affecting the decisions of the metal market's stakeholders.

3. Methodology

3.1. Price convergence theory

With respect to the commodity markets, the price behaviour theory connotes that prices will be auto-correlated, convergent series. This idea arises from the organic make-up of commodity production and storage and the costs of arbitrage in the course of time. For instance, products are periodically produced and endlessly consumed with the associated costs of storage engendering auto-correlated prices (Wang and Tomek, 2007). Combine with the foregoing idea is the structural changes in the market as result of a shift in the fundamental functioning of the market due to changes in (a) when divergence occurred between the policies of the U.S Federal Reserve and other Central Banks (differences in Central Bank policies leading to uncertainties in metals' prices (b) reduction in gold consumption by China (c) instability of the European Union (EU) and (d) increasing accumulation of Gold reserves by major Central Banks. Similarly, there could be nonlinearity in market prices adjustment when such prices are not closely proportional to measure of quantity demand. Some of the causes of non-linear adjustment of prices are market frictions, transaction costs (bid-ask spread, short selling, and borrowing constraints), heterogeneous agents' interactions and beliefs (Hasanov and Omay, 2007). Thus, it is difficult to arbitraged way the systematic behaviour in metals' prices (Wang and Tomek, 2007). All these distortion of prices need to be studied and taken into consideration when analyzing price behaviour so as to aid evidence-based decision making by various market participants.

In the same vein, market prices can deviate from their fundamental values, this is known as price bubble (Khan and Köseoğlu, 2020; and Su et al., 2017). Price bubble is reflected as a break in asset prices that is characterized by significant downward or upward price movements (Phillips and Shi, 2020). A number of factors have been identified as causes of price bubbles including speculation, currency movement, supply and demand conditions, interest rate, financial crisis and climate change (Su et al. 2017, 2020). Given that bubble incidences distort the decisions of the market participants, there is need for monitoring, studying and analyzing market prices so as to provide early warning signals to stakeholders.

Pindyck (1993) described bubble as the present value model which is the addition of the current and discounted expected future payoff of asset and it is expressed as:

$$P_t = \frac{E_t(P_{t+1} + \xi_{t+1})}{1+R} \tag{1}$$

Where P_t is the price of metals which is equal to payoffs and total discounted future prices; ξ_t represents convenience yield, while discount rate is denoted by R.

The above equation (1) is considered a dynamic model because it illustrates the variations in commodity prices while the storage value is assumed to be positive. Also, it takes both demand and supply sides into consideration (Pindyck, 1993). Finally, equation (1) is estimated together with the law of iterated expectations as:

$$P_t = P_t^f + b_t \tag{2}$$

Where P_t^f denotes the fundamental price while b_t represents the bubble factor. Equation (2) shows that market fundamental (P_t^f) and (b_t) are the two components that metals' prices comprise. The model also shows that when $b_t = 0$, the prices of metals P_t fully dependent on P_t^f. However, when $b_t \neq 0$, the prices of metals are also affected by b_t. This phenomenon according to Campbell et al. (1998) is referred to as a rational bubble because the expression in equation (2) can be used to detect if the prices of metals surpass its fundamental prices as well as showing rational expectations.

3.2. Estimation methods

3.2.1. Conventional or traditional unit root tests

This study considers two conventional unit root tests, which are the Augmented Dickey Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. The detailed mathematical discussions of each are given in Dickey and Fuller (1979) and Kwiatkowski et al. (1992). In case these tests provide results that show non-stationary of the series, tests for possibility of structural breaks in the price series and checking their linearity status should be conducted, as recent development in time series econometrics methods has revealed the need to account for these two inherent features of data when analyzing their unit root property (Solarin and Lean, 2016; Adewuyi et al., 2020).

3.2.2. Tests for detecting structural breaks (SB) and linearity status

The Bai and Perron (2003) SB unit root test technique is based on multiple linear regression model with m breaks (m + 1 regimes).

$$y_t = x_t^{'}\beta + z_t^{'}\delta_j + \mu_t \quad t = T_{j-1}+1, \ldots, T_j \tag{3}$$

Given that j = 1, …, m + 1, the observed dependent variable at time t is denoted by y_t; x_t(p x 1) and z_t(q x 1) represent the vectors of covariates while β_j and δ_j (j = 1, …, m + 1) are the associated vectors of coefficients; the error term at time t is represented by μ_t. The indices $(T_1, \ldots, T_m)$ which captured the break points are treated as unknown given that $(T_0 = 0)$ and $(T_{m+1} = T)$. This enables estimating the unknown regression coefficients together with the break points when T observations on x_t, y_t and z_t are accessible. The parameter vector β is considered a partial structural change model since it is not subjected to changes and its estimation is based on the whole sample. To derive a pure structural change model in which all the coefficients are subject to variation, we set ρ = 0. The variance of μ_t needs not be constant, in effect, breaks in variance are allowed if they occur at the same dates with the breaks in the regression's parameters.

Equation (3) may be expressed in matrix form as

$$Y = X\beta + \widetilde{Z}\delta + U \tag{4}$$

Where $Y = (y_1 \ldots\ldots y_T)^{'}, X = (x_1 \ldots\ldots x_T)^{'}, U = (u_1 \ldots\ldots u_T)^{'}, (, \delta_1^{'}, \delta_2^{'} \ldots\ldots \delta_{rm+1})^{'}$ and $\breve{Z}$ is the matrix which diagonally partitions Z at $(T_1, \ldots, T_m)$, that is, $\breve{Z} = \text{diag}\ (Z_t \ldots\ldots Z_{m+1})$ with $Z = (ZT_{j-1} + 1, \ldots\ldots T_j^{'})^{'}$.. The true value of a parameter is represented with a 0 superscript. Also, the true values of the parameters ν is given by $\delta^{0^{'}} = (, \delta^{0^{'}}{}_1, \delta^{0^{'}}{}_2, \ldots\ldots \delta^{0^{'}}{}_{rm+1})$ while the true break points is denoted by $(T_1^0 \ldots\ldots\ldots T_m^0)^{'}$.$Z$ is diagonally partitions at $(T_1^0 \ldots\ldots T_m^0)$ by the matrix $\breve{Z}'0$, thus, the data-generating process is taken to be as follows;

$$Y = X\beta^0 + \widetilde{Z}^{'0}\delta^0 + U \tag{5}$$

The method of estimating equation (5) above is guided by the least-squares principle. For each m-partition $(T_1, \ldots\ldots T_m)$, it is required that the sum of squared residuals must be minimised so as to get the corresponding least-squares estimates of β *and* δ. The efficiency of the least-squares method proposed above to achieve a global minimum is determined by the appropriate choice of the initial value of the vector β to begin the iteration process. The procedure required in getting the initial value of the vector β is well explained in Bai and Perron (2003). Concerning estimating the number of breaks, Bai and Perron (2003) proposed a sequential application of the sup $F_r(e+1/e)$ test based on the sequential estimates of the breaks. If the sum of squared residuals from the (e) breaks model is greater than the overall minimum sum of squared residuals, a rejection in favour of a model with (e+1) breaks is settled for. Therefore, the break date chosen is the one corresponding to this overall minimum. Asymptotic critical values were provided by Bai and Perron (2003).

There is need to test for the linearity status of commodity prices (as stated earlier) given that such prices may be disproportional to the measure of volume demanded as a result of market frictions, transaction costs and interactions and belief of heterogeneous market participants (Hasanov and Omay, 2007). For testing the linearity status of series particularly when the order of integration is unknown, this study adopts Harvey et al. (2008) who consider a non-linear AR (1) model for an I (0) time series $y_t, t = 1, ..., T$

$$\begin{gathered} y_t = \mu + \upsilon_t, \\ \upsilon_t = \rho\upsilon_{t-1} + \delta f(\upsilon_{t-1}, \theta)\upsilon_{t-1} + \varepsilon_t \end{gathered} \tag{6}$$

where ε_t is a zero mean *IID* white noise process that possesses finite moments up to order 12 (as in assumption 1 of Harvey and Leybourne, 2007), and where ρ, δ and the function $f(., \theta)$ are chosen such that υ_t is stationary globally. If the function $f(., \theta)$ follows a Taylor series expansion around $\theta = 0$, estimation of this model to the second order can be expressed as:

$$\begin{gathered} y_t = \mu + \upsilon_t \\ \upsilon_t = \delta_1\upsilon_{t-1} + \delta_2\upsilon_{t-1}^2 + \delta_3\upsilon_{t-1}^3 + \varepsilon_t \end{gathered} \tag{7}$$

Following this framework, the null hypothesis of linearity and alternative of nonlinearity **in the case where the series are stationary *(I(0))*** can be stated as:

$H_{0,0} : \delta_2 = \delta_3 = 0$

$H_{1,0} : \delta_2 \neq 0$ and/or. $\delta_3 \neq 0$

The standard Wald statistic for testing these restrictions is given by:

$$W_0 = T\left(\frac{RSS_0^r}{RSS_0^u} - 1\right)$$

Where RSS_0^r and RSS_0^u represent the residual sum of squares from the restricted and unrestricted OLS regression. Therefore the standard large sample theory shows that W_0 follows an asymptotic $X^2(2)$ distribution under the null $H_{0,0}$ while under the non-linear alternative $H_{1,0}$, it diverges at the rate $O_p(T)$.

On the other hand, the null hypothesis of linearity and alternative of nonlinearity for series that are non-stationary *(I(1))* can be stated as:

$H_{0,1} : \vartheta_2 = \vartheta_3 = 0$

$H_{1,1} : \vartheta_2 \neq 0$ and/or. $\vartheta_3 \neq 0$

Also, the standard Wald statistic for testing these restrictions is given by:

$$W_1 = T\left(\frac{RSS_1^r}{RSS_1^u} - 1\right)$$

Where RSS_1^r and RSS_1^u represent the residual sum of squares from the restricted and unrestricted OLS regression while T is the number of observations.

In a situation where it is difficult to make a precise decision regarding the order of integration of series (unknown unit root status), Harvey et al. (2008) proposed an innovative approach.[10] Using this approach to determine the linearity structure of such series, we apply a test which asymptotically computes W_0 statistic when the data are assumed to be stationary, and the W_1 statistic when the data are assumed to be non-stationary and derives a weighted mean statistic (W_λ) from the two statistics. Thus, this method is regarded as a weighted average statistical method, which is computed as:

$$W_\lambda = \{1 - \lambda\}W_0 + \lambda W_1 \tag{8}$$

Where λ is some function that converges in probability to zero when the series is stationary *(I(0))* and to one when the series is non-stationary *(I (1))*. This denotes that under the null of either *I(0)* or *I(1)* linearity, W_λ Chooses the efficient test in the limit, and is asymptotically distributed as chi-square with two degrees of freedom.

3.2.3. Nonlinear unit root test with structural break

In this study, a unit root test that accommodates multiple endogenous temporary (smooth) breaks and non-linear mean reversion developed by Christopoulos and Leon-Ledesma (C-L), 2010)) is employed. The C-L (2010) test is based on Fourier function in the first stage (to model structural break) and the Kapetanios, Shin, and Snell (KSS) test in the second stage (to capture the nonlinear adjustment), thus allowing the modeling both data features together. The C-L (2010) test procedure involves the use of trigonometric variables in which significant variations in the variable's mean is captured alongside the smooth transition functions that allow the non-linear adjustment to its deterministic component. The C-L (2010) test is based on trigonometric function to model breaks so that changes in the mean are transitory, and thus the beginning and end values are managed to converge. Using this function, the breaks modeled are rather smooth changes and not jump functions.

Considering the following model for a stochastic variable g_t

$$g_t = \delta(t) + \varepsilon_t \tag{9}$$

$\delta(t)$ denotes the time-varying deterministic component while ε_t is the independent and identically distributed with zero mean and constant variance. Following studies such as Enders and Lee (2004); Becker et al. (2004) and Becker et al. (2006), a Fourier series expansion is applied in order to estimate the unknown number of breaks $\delta(t)$. In a general form, the unknown term can be expanded as given in equation (10);

$$\delta(t) = \delta_0 + \sum_{k=1}^{k}\delta_1^k Sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=2}^{k}\delta_2^k Cos\left(\frac{2\pi kt}{T}\right) \tag{10}$$

Where T is the sample size, k denotes the number of frequency of the Fourier function, t represents the trend term and $\pi = 3.142$.

Identifying the appropriate number of frequencies to be included in the fitted model is the specification problem inherent in equation (10). This problem can be addressed by following Ludlow and Enders (2000) who show adequacy of a single frequency in approximating the Fourier expansion in empirical applications. Therefore, equation (10) can be rewritten as:

$$\delta(t) = \delta_0 + \delta_1 Sin\left(\frac{2\pi kt}{T}\right) + \delta_2 Cos\left(\frac{2\pi kt}{T}\right) \tag{11}$$

A standard approach to obtain the most appropriate value of k is to estimate equation (9) under definition of equation (11) for each integer value of k in the interval 1–3. In this study, the optimal value of k for the period ranged between 1 and 2 for the Fourier functions when equation (10) is estimated under definition in equation (10) with a sample period T = 7766 for daily data and T = 1617 for weekly data. In general, three

[10] Where series are subjected to several unit root tests, some would not be stationary using the conventional unit root tests but stationary using nonlinear unit root tests.

(3) procedures are required to follow for this estimation.

Step 1. Determine the optimal frequency k*. This is done by estimating equation (11), with the inclusion of the error term, by OLS for values of k between 1 and 3 and then selects the one that minimizes the residual sum of squares. Subsequently, the OLS residuals are computed as;

$$\widehat{\varepsilon} = Metal_t - \widehat{\delta}_0 + \widehat{\delta}_1 Sin\left(\frac{2\pi k^* t}{T}\right) + \widehat{\delta}_2 Cos\left(\frac{2\pi k^* t}{T}\right) \tag{12}$$

Step 2. Carry out a unit root test on the OLS residual initially obtained in step one. Given the fact that the results of the test may show mean reversion which may be non-linear due to transaction costs or heterogeneous expectations of metal markets' participants, this study employed the following linear and non-linear models proposed by C -L (2010);

$$\Delta\varepsilon_t = \alpha_1 \varepsilon_{t-1} + \sum_{j=1}^{p} \beta_j \Delta\varepsilon_{t-j} + \mu_t \tag{13}$$

$$\Delta\varepsilon_t = \rho\varepsilon_{t-1}\left(1 - \exp\left(-\theta\Delta\varepsilon_{t-i}^2\right)\right) + \sum_{j=1}^{p} \beta_j \Delta\varepsilon_{t-j} + \mu_t, i = 1, 2, ...L, \tag{14}$$

$$\Delta\varepsilon_t = \varphi_1 \varepsilon_{t-1}^3 + \sum_{j=1}^{p} \beta_j \Delta\varepsilon_{t-j} + \mu_t \tag{15}$$

Where, $\theta > 0$ and μ_t is the error term.

Step 3. The decision rule is that, if the null hypothesis of a unit root in step two is rejected, the third step consists of testing for $H_0 = \delta_1 = \delta_2 = 0$ against the alternative $H_1 = \delta_1 = \delta_2 \neq 0$ in equation (11) using the F-test $F_\mu(\widetilde{k})$. If the null hypothesis is rejected, then we conclude that the variable is stationary around a breaking deterministic function.

As an alternative to C-L (2010), the unit root test developed by Guris (2018) also accounts jointly for structural breaks and nonlinear adjustment that relies on modified ESTAR model. The structural breaks are modeled by means of a Fourier function while nonlinear adjustment is modeled by means of an ESTAR model proposed by Kruse (2011). The unit root test by Kruse (2011) is an advanced version of the test introduced by Kapetanios, Shin, and Snell- KSS (2003). The KSS (2003) used the non-linear stationary exponential smooth transition autoregressive (ESTAR) model with a zero location parameter (with the null hypothesis of 'unit root''). The ESTAR model is expressed as:

$$\varepsilon_t = \beta y_{t-1} + \phi y_{t-1}\left[1 - \exp\left\{-\theta(y_{t-1} - c)^2\right\}\right] + \mu_t \tag{16}$$

In contrast, Kruse (2011) employed ESTAR model with the possibility of non-zero location parameter($c \neq 0$).with null hypothesis of "stationary''. Based on this, equation (12) in the C-L (2010) is transformed using the Taylor approximation in the Kruse (2011) as follows:

$$\Delta\varepsilon_t = \varphi_1 \varepsilon_{t-1}^3 + \varphi_2 \varepsilon_{t-1}^2 + \sum_{j=1}^{p} \beta_j \Delta\varepsilon_{t-j} + \mu_t \tag{17}$$

Thus, although the ESTAR model differs, the procedure for unit root test originated by Guris (2018) are the same three (3) stages stated above for operationalising the C-L (2010) test.

3.2.4. Bubbles detection method

The newly articulated test by Phillips and Shi (2019) provide a precise tactic for measuring explosive and dynamic bubbles in asset prices. The 'right-sided' unit root test has been found to be excellent at suitably identifying periods of explosive bubbles compared to the standard unit root tests, particularly when there are multiple periods of price explosion over a period of time.

A more efficient procedure upon which Phillips and Shi (2018) is based follows the recursive rolling window of Phillips et al. (PSY, 2015a, b). This is mostly used to determine the presence of multiple bubbles over a sample period.

Each of the observations of interest (ranging between r_0 and 1) can easily be tested using PSY procedure. The suggested setting of $r_0 = 0.01 + 1.8/\sqrt{T}$, where T is the size. Supposing that r is the interested observation, the PSY calculates the ADF statistic from a backward expanding sample series. Assuming the start and end points of the regression sample are given by r_1 and r_2, the calculated ADF statistic from this sample is $ADF_{r_1}^{r_2}$. While allowing variation for start point r_1 within the range $[0, r - r_0]$, the end point of all samples on the observation of interest is fixed such that. $r_2 = r$.

The following equation under the null hypotheses of $\rho = 0$ can be estimated as:

$$\Delta y_t = \mu + \rho y_{t-1} + \sum_{j=1}^{p} \varphi_j \Delta y_{t-j} + \gamma_t \tag{18}$$

The ultimate values of all ADF statistics are the PSY statistics which is given in equation (19) as:

$$PSY_r(r_0) = \sup_{r_1 \in [0, r-r_0], r_2 = r} \left\{ADF_{r_1}^{r_2}\right. \tag{19}$$

The decision rule is that when the exuberance date which is considered to be where the PSY test statistics is greater than its critical value. This is considered as the first stopping period for this episode. Equally, the collapse date is assumed to be when the supremum test statistics is less than its essential value. This episode is considered the second stopping period. Assuming only one episode of the sample exists which originates from r_e to r_f, the estimated periods and termination dates as suggested by Phillips and Shi (2018) are given by equations (20) and (21);

$$\widehat{r}_e = \inf_{r_1 \in [r_0, 1]} \{r : PSY_r(r_0) > cv_r(\beta_T)\} \tag{20}$$

$$\widehat{r}_f = \inf_{r_1 \in \left[\widehat{r}_e, 1\right]} \{r : PSY_r(r_0) < cv_r(\beta_T)\} \tag{21}$$

Where the quantile of the distribution of the $PSY_r(r_0)$ of equation (18) is represented by $cv_r(\beta_T)$.

3.3. Data description and sources

This study utilizes both daily and weekly world price data available for five metals for the period April 4, 1990 to March 28, 2021. The metals considered in this study are gold, palladium, platinum and silver which are measured in USD per troy ounce and copper which is measured in USD per metric ton. The daily data used for the analysis spanned from April 2, 1990 to March 26, 2021 while the weekly data spanned from April 8, 1990 to March 28, 2021. Data for copper were sourced from https://www.investing.com/commodities/copper while data for gold, palladium, platinum and silver were sourced from https://www.quandl.com/data/LBMA-London-Bullion-Market-Association.

4. Results and discussion

4.1. Descriptive statistics

Gold, palladium and platinum are the metals whose daily and weekly prices are considerably higher than $1000 per troy ounce during the period (Table 1). It is also observed that the prices of these metals except copper and silver have larger standard deviation. This connotes that the degree of volatility in the prices of gold, palladium and platinum is high. Moreover, three distribution tests which include skewness, kurtosis and jarque-Bera are reported. In the case of skewness test, which measure the asymmetry of the distribution of the series, the test results show that

Table 1
Descriptive statistics.

Metals	Mean	Median	Max	Min	Std. Dev	Skewness	Kurtosis	Jarque-Bera	Observations
Daily data									
Copper	2.0214	1.6750	4.6230	0.6040	1.1213	0.3091	1.6044	753.917***	7766
Gold	783.808	461.200	2067.15	252.800	503.851	0.5808	1.8582	858.524***	7766
Palladium	520.064	350.000	2781.00	78.2500	487.968	2.0772	7.7817	12983.34***	7766
Platinum	863.210	842.000	2273.00	330.750	451.312	0.6125	2.3456	624.118***	7766
Silver	12.013	7.6500	48.7000	3.5475	8.5579	1.1222	3.7474	1810.84***	7766
Weekly data									
Copper	2.0137	1.6250	4.5710	0.6120	1.1225	0.3255	1.6192	157.023***	1617
Gold	784.179	462.650	2031.15	253.800	503.547	0.5783	1.8559	178.319***	1617
Palladium	520.786	350.500	2719.00	78.2500	488.485	2.0737	7.7758	2695.69***	1617
Platinum	862.867	838.000	2182.00	331.500	450.721	0.6137	2.3524	129.749***	1617
Silver	12.0168	7.6700	48.7000	3.5665	8.5532	1.1314	3.8203	390.307***	1617

Source: computed. Note: ***, ** and * imply significant at 1%, 5% and 10%, respectively.

both daily and weekly prices of all metals are positively skewed as the values for these metals are greater than zero. This implies that prices of these metal have high probability of exhibiting extreme positive values than extreme negative values. The kurtosis statistics, which measures the peakedness or flatness of the distribution of the series, indicates that prices of these metals are highly platykurtic as kurtosis statistics of some of the series are less than 3, except the price of palladium and silver. Finally, the Jarque-Bera test is statistically significant for all the metal prices during the period. This implies that the null hypothesis of normality for these varieties of metals can be rejected.

The trends of prices of the metals can be seen from Figs. 1 and 2. The figures reveal the volatility of prices of the metals and the reflection of potential structural changes and nonlinearity of the prices during the study periods.

4.2. Results of the conventional unit root tests

This sub-section presents the results of the two conventional unit root tests (ADF and KPSS) conducted in this study. The two tests have different hypothesis, with the null hypothesis of ADF test stated as "*there is unit root*'' while that of the KPSS test is stated as "*there is stationarity*". In each of these two conventional unit root tests performed, consideration was given to the null hypothesis "with intercept and trend'' in order to determine stationary or not for each of the prices of metals being analysed. With respect to ADF test, the null hypothesis is accepted for all the metals' prices (Table 2a). This implies that prices of all the metals are not stationary at level [(I(1)]. Concerning the KPSS test, the null hypothesis of stationarity is rejected in favour of non-stationary of all the metals' prices at 1 percent level of significance. The summary results of the two conventional unit root tests presented in Table 2b show that none of the metals' prices is stationary using both daily and weekly data sets for the period. These results are consistent with some earlier studies such as Narayan and Liu (2011) and Adewuyi et al. (2020).

4.3. Analysing structural breaks (SB) and linearity status of the series (variables)

As stated earlier, the conventional unit root tests provide unreliable results when time series data are characterized by structural breaks and nonlinearity as the tests lack power to handle nonlinear stationarity (Solarin and Lean, 2016; Adewuyi et al., 2020). It is therefore imperative to test the existence of these two potential features of prices of the metals.

The Bai and Perron (2003) SB test, based on daily and weekly data sets, indicates that prices of the metals have five (5) different SB dates (Table 3). Using both daily and weekly data sets, the SB dates for prices of all the metals do not follow the same pattern. The SB dates for daily data fells between November 19, 1997 and October 10, 2018 while they cover between February 15, 1998 and September 22, 2019 for weekly data. The incidence during the earlier dates for both daily and weekly data coincided with the event in 2017 when divergence occurred between the policies of the U.S Federal Reserve and other Central Banks (differences in Central Bank policies leading to uncertainties is a major reason for high volatility in metals' prices), reduction in gold consumption by China, instability of the European Union (EU), and increasing Gold reserves of Central Banks. The later date for weekly data, particularly in 2019 coincided with the progress in the US-China trade war negotiations[11] and as well the incidence of banking instability in China and India.[12] The later date for daily data coincided with the period when the U.S. Dollar Index belonging to six of the US' biggest foreign-trade partners collapsed to the lowest levels.[13] Also, since gold is dollar-denominated, it becomes increasingly expensive for non-US investors because weak US dollar makes gold price to rise. This in turn has forced the non-US investors to scale down their demand for the precious metal.[14]

In an attempt to examine the linearity properties of the metals' prices, this study adopts Harvey et al. (2008) method with the null hypothesis of linearity against the alternative of non-linearity. The results in Table 4 show that both daily and weekly prices of all the metals have non-linear pattern. These results are consistent and robust for analysing the linearity structure of the prices. Thus, examination and analysis of the unit root property of the metals' prices require paying attention to their non-linear structure.

In terms of suitable unit root test to be applied, it is clear that during the period, unit root test that accounts for both structural breaks and non-linearity structure (i.e., either C-L, 2010 test or Guris, 2018 test) could be applied for all the metals' prices.

4.4. Results of non-linear unit root tests with structural breaks

The unit root properties of prices of the metals are also examined with methods that account for both non-linearity and structural break (Christopoulos and Leon-Ledesma: C-L, 2010 and Guris, 2018). For C-L (2010) test, the results reveal that the null hypothesis of non-stationary is rejected for all prices of the metals (Table 5). This implies that both daily and weekly prices of all the metals are stationary. Equally, the results of the Guris (2018) test show that the null hypothesis of stationarity is accepted except for Silver (Table 6). This implies that the metals' prices (both daily and weekly) are also stationary using this

[11] https://www.china-briefing.com/news/the-us-china-trade-war-a-timeline/.
[12] http://mtsgold.com/en/research/detail.php?ID=18948&SECTION_ID=21.
[13] The U.S. Dollar Index measures the value of the dollar against a weighted basket of currencies belonging to six of the US' biggest foreign-trade partners (the euro, yen, pound sterling, Canadian dollar, Swedish krona and Swiss franc).
[14] https://internationalbanker.com/brokerage/why-gold-prices-have-disappointed-in-2018/.

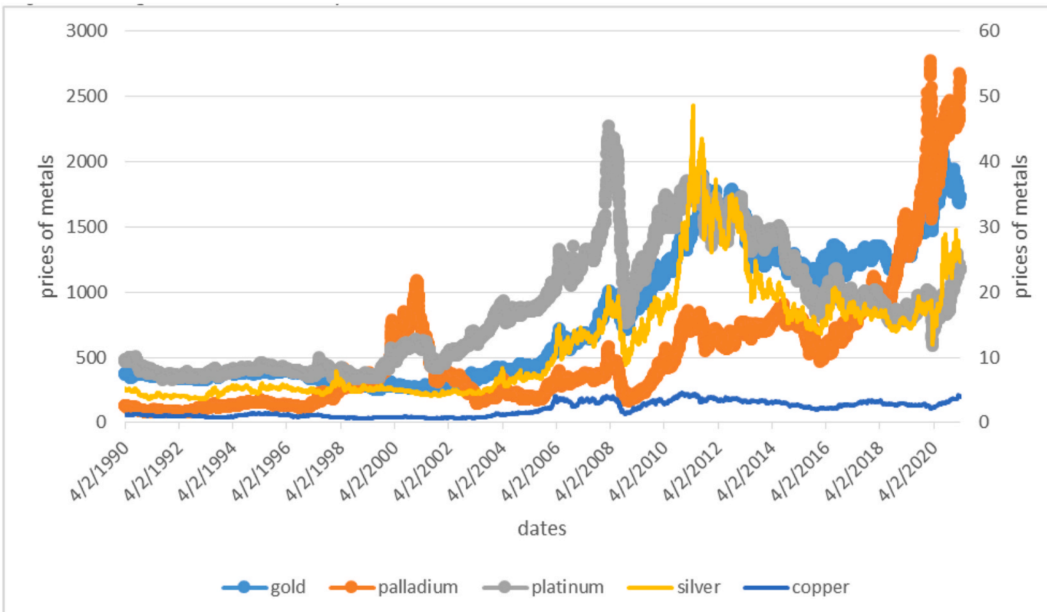

Fig. 1. Depicted are the Daily Prices of Metals.

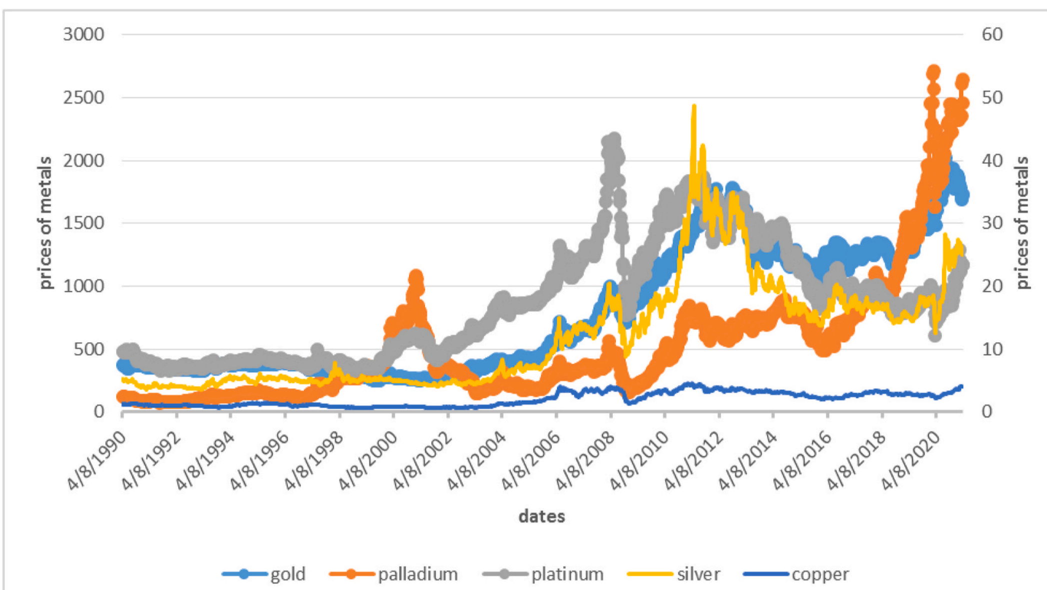

Fig. 2. Depicted are the Weekly Prices of Metals.

approach. Hence, the overall summary result or decision is that metals prices are stationary based on the results of the two tests. The results also suggest that non-linear and structural breaks processes embedded in the prices of all the metals should be considered when testing them for stationarity. These results are in line with Adewuyi et al. (2020) who tested unit root for both industrial and precious metals.

It should be noted that, although both tests performed well with daily data, Guris (2018) test performed better than the C-L (2010) test when considering weekly data (see Tables 5 and 6).

4.5. *Identification and analysis of crisis and bubble incidences*

In the gold market, two short, mildly explosive episodes were detected in July–September 1997, while a positive, mildly explosive episode was detected between October 1997 and January 1998 (Table 7a). This can be explained by the taxpayer Relief Act which the US Congress passed in July 1997. According to this Act, every Individual Retirement Account holders was permitted to buy gold bullion of purity 99.5% and above for their accounts. This is presumed to be an important event for the world gold market. Also, the empirical results show three short, mildly explosive episodes in gold prices in 1999: the first occurrence started from June 13 to 27, 1999, the second occurrence took place between July 11 and August 8, 1999, while the third episode spanned between August 22 and September 19, 1999. The first two episodes could be explained by the adoption of a single currency by eleven of the fifteen countries of the European Union. The European Monetary Union therefore led to the creation of an economic area similar in size to that of the US and backed by the European Central Bank. The birth of a rival currency to dollar was considered to have implications for gold price as it becomes attractive as a hedge asset for

Table 2a
Conventional Unit Root Tests at Levels.

Method	ADF		KPSS	
Daily data				
Metals	Intercept only	Intercept and trend	Intercept only	Intercept and trend
Copper	−0.947184 (0.7736)	−2.237876 (0.4677)	7.794452***	0.888330***
Gold	−0.560936 (0.8767)	−2.178336 (0.5011)	9.514388***	1.296389***
Palladium	1.080547 (0.9974)	−0.389022 (0.9880)	6.603825***	1.186315***
Platinum	−1.822301 (0.3700)	−2.146542 (0.5190)	6.993301***	1.486026***
Silver	−1.413996 (0.5770)	−2.554298 (0.3017)	7.489643***	0.760468***
Weekly data				
Copper	−0.987615 (0.7596)	−2.311914 (0.4266)	3.467092***	0.406104***
Gold	−0.060866 (0.9517)	−2.006114 (0.5970)	4.169018***	0.574024***
Palladium	0.699354 (0.9922)	−0.894904 (0.9549)	2.991761***	0.546560***
Platinum	−1.502842 (0.5322)	−1.970420 (0.6165)	3.094312***	0.672432***
Silver	−1.533799 (0.5163)	−2.720808 (0.2282)	3.308748***	0.342029***

Source: computed. Note: the optimal lag selection for conventional unit (i.e. ADF) is based Schwarz Information criterion with maximum lag at 1, while the spectral estimation of KPSS is based on Bartlett kernel default. ***, ** and * indicate significant at 1%, 5% and 10%, respectively. The p-values from the ADF tests are given in parentheses, while KPSS reports the critical values alone. The critical values for KPSS tests are given at 1% for the models with intercept alone and intercept and trend as 0.7390 and 0.2160.

Table 2b
Summary Results and Decision for Conventional Unit Root Tests at Levels

Method	ADF	KPSS	Decision
Daily data			
Copper	I(1)	I(1)	I(1)
Gold	I(1)	I(1)	I(1)
Palladium	I(1)	I(1)	I(1)
Platinum	I(1)	I(1)	I(1)
Silver	I(1)	I(1)	I(1)
Weekly data			
Copper	I(1)	I(1)	I(1)
Gold	I(1)	I(1)	I(1)
Palladium	I(1)	I(1)	I(1)
Platinum	I(1)	I(1)	I(1)
Silver	I(1)	I(1)	I(1)

Source: computed from Table 2a above.

investors in case the rival starts to challenge the dominance of dollar and eventually unseats dollar from its preeminent position.

The third episode which occurred between August 22 and September 19, 1999 could be ascribed to widespread concern that uncoordinated central bank gold sales had destabilized the gold market by sharply driving down the prices. As a response to these concerns in September 1999, 15 European central banks, accounting for 45% of global gold reserves, signed an agreement in Washington DC to collectively limit their gold sales to 2000 tonnes over five years, or around 400 tonnes a year. Between April and May 2006, a short, mildly explosive episode was detected in gold price. Higher increase in gold price during the period could be explained by the Iran nuclear crisis which arose with the breaking of UN seals at the Natanz uranium enrichment plant in January 2006 and ended with the unanimous approval of the UN Security Council sanctions intended to curb Iran's nuclear program. Consequently, a total ban was imposed on import and export of materials and technology used for uranium enrichment or reprocessing and for the production of ballistic missiles. The dollar depreciated by almost 11%

Table 3
Extracted Results of the Bai-Perron (2003)'s Structural break tests with multiple breakpoints.

Metal type	Period	Time Break
Daily data		
Copper	5	11/20/2002, 8/15/2005, 1/15/2008, 7/01/2010, 11/17/2015
Gold	5	2/05/2003, 3/19/2008, 12/01/2010, 4/14/2015, 9/12/2017
Palladium	5	11/19/1997, 3/07/2001, 7/21/2009, 9/19/2014, 1/05/2018
Platinum	5	5/16/2001, 7/21/2006, 1/18/2008, 7/15/2010, 8/27/2014
Silver	5	1/22/2004, 2/05/2008, 6/28/2010, 3/26/2014, 10/10/2018
Weekly data		
Copper	5	6/08/2003, 4/16/2006, 10/12/2008, 5/01/2011, 11/13/2016
Gold	5	7/06/2003, 10/19/2008, 8/07/2011, 2/07/2016, 8/05/2018
Palladium	5	2/15/1998, 7/22/2001, 3/07/2010, 7/12/2015, 11/25/2018
Platinum	5	9/30/2001, 2/04/2007, 8/17/2008, 3/13/2011, 6/21/2015
Silver	5	7/11/2004, 9/07/2008, 2/27/2011, 1/11/2015, 9/22/2019

Source: Extracted from Table 1 in Appendix A.

Table 4
Results of Linearity test (Harvey et al. 2008).

Variable	$W_\lambda$statistic	Linearity structure
Daily data		
Copper	12.958	Nonlinear
Gold	6.989	Nonlinear
Palladium	26.886	Nonlinear
Platinum	6.781	Nonlinear
Silver	17.625	Nonlinear
Weekly data		
Copper	8.931	Nonlinear
Gold	5.528	Nonlinear
Palladium	9.669	Nonlinear
Platinum	7.749	Nonlinear
Silver	15.449	Nonlinear

Source: Authors' computation. The rejection of the null hypothesis of linearity at 1%, 5% and 10% are 70.06, 77.93 and 82.36, respectively. *, ** and *** represent 1%, 5% and 10% significant levels. Note: this study assumed the value of $\lambda$to be 0.3 as an option used in Harvey et al. (2008).

Table 5
Non-linear unit root tests with breaks (Christopoulos and Leon-Ledesma (C-L), 2010)) based on KSS (2003) with unit root null hypothesis.

Variable	k	Fu(k)	FADF	F-tiN	F-Sup_tiN
Daily data					
Copper	1	10897.04	−1.694 (0.434)	17.177***	−3.402***
Gold	1	11718.01	−1.438 (0.565)	4.771***	4.661***
Palladium	1	1300.937	0.450 (0.985)	8.184***	−5.486***
Platinum	1	20758.02	−2.743 (0.067)*	5.932***	5.392***
Silver	1	8013.207	−2.575 (0.098)*	27.191***	8.395***
Weekly data					
Copper	1	2334.47	−1.868 (0.3478)	8.065***	5.521***
Gold	1	2552.93	−1.146 (0.6994)	5.698***	−18.794***
Palladium	1	284.681	0.019 (0.9591)	5.323***	−21.695***
Platinum	1	4324.23	−3.162 (0.0225)**	−3.389***	−15.846***
Silver	1	1671.39	−2.713 (0.0720)*	13.095***	13.005***

Source: Author(s) estimation from E-view 10. Note> (***), (**) and (*) indicate rejection of the null unit root hypothesis at the 1%, 5% and 10% significance level, respectively. The underlined figures signify rejection of the null of linearity at conventional significance levels. The Fu(k) test is distributed as an F-statistic under the null hypothesis with 2 degrees of freedom for selected equation that minimizes the residual sum of squares.

Table 6
Non-linear unit root tests with breaks (Guris, 2018) based on Kruse (2011) with stationarity null hypothesis.

Variable	k	Fu(k)	FADF	F-tiN	F-Sup_tiN
Daily data					
Copper	1	10897.04	−1.694 (0.434)	17.177	2.346
Gold	1	11718.01	−1.438 (0.565)	4.771	3.927
Palladium	1	1300.937	0.450 (0.985)	8.183	3.696
Platinum	1	20758.02	−2.743 (0.067)*	5.932	7.013
Silver	1	8013.207	−2.575 (0.098)*	27.191***	−3.665
Weekly data					
Copper	1	2334.47	−1.868 (0.3478)	8.065	−1.859
Gold	1	2552.93	−1.146 (0.6994)	5.698	5.698
Palladium	1	284.681	0.019 (0.9591)	5.323	3.209
Platinum	1	4324.23	−3.162 (0.0225)**	1.021	7.116
Silver	1	1671.39	−2.713 (0.0720)*	13.095*	13.095*

Source: Author(s' computations Note: (1) The critical values for Kruse test with Fourier approximation when sample size (T) ≥ 500 are 23.26, 20.4 and 19.12 at 1%, 18.14. 16.08 and 14.6 at 5% while 15.8, 13.64 and 12.44 at 10%. When T ≤ 250, the critical values are 23.56, 20.02 and 18.78 at 1%, 18.14, 15.74 and 14.2 at 5% while 15.74, 13.5 and 12.32 at 10%. For T ≤ 50, the critical values are 24.24, 22.34 and 19.26 at 1%, 18.38, 15.62 and 13.96 at 5% while 15.66, 13.16 and 11.62 at 10%, respectively.
(2) All prices of the metals are stationary at 1%.

against the British pound and 8.9% against the Euro and gold price appreciated by almost 14.6% during this crisis period.[15] Furthermore, a short, mildly explosive episode in gold price in 2020 spanned between July 26 and August 16, 2020. This higher increase in gold price during this period could be explained by the oil price fall and decline in global stock markets. Owing to the global spread of COVID-19 pandemic, there was significant fall in oil price and stock markets in the entire world. During this period with deep economic crisis in the world, gold price rapidly moved above US$ 1,700.[16] Given these circumstances, investors considered gold as safe haven and thus shift their investment towards it.

In the palladium industry, a short, mildly explosive episode was detected from October 7 to November 2001. This could be explained mainly by the supply disruption in Russia, in which significant pressure was exerted on its price during the period. Russia being the largest producer and almost 40% of the world supply of palladium. Moreover, a mildly, explosive episode was detected spanning from March 16 to June 29, 2003. This rise in price of palladium could be as a result of its valuable combination of intrinsic mechanical and physical properties that palladium possesses make it unique among the precious metals.[17] Another short, positive, mildly explosive which occurred between September 14 and October 26, 2008 could be explained by increased demand for palladium by 3.5% to a total of 6.84 million ounces.[18] During this period, the use of palladium by automotive manufacturers was encouraged where possible due to a favourable price ratio between platinum and palladium in their catalytic converters – both diesel and gasoline. As a result, palladium production grew up and its demand also increased significantly.[19] Between January 11, 2016 and February 28, 2020, a short, mildly explosive episode was detected in the palladium industry. This could be explained by the increasing demand for gasoline-powered cars that use palladium devices, particularly in Europe. It was discovered that a lot of diesel car companies, which use devices that are non-palladium based, were dishonest about their emissions tests. Consequently, gasoline-powered cars that are palladium rooted have become more popular[20].

For platinum, bubble is detected for the period from February 17 to March 16, 2008, and from October 19 to November 2, 2008. This increase in the price of platinum during the early period of 2008 could be explained partly by supply shortage in 2007 which dropped by 4.1% to 6.55 million ounces. Also, a combination of issues that occurred in South Africa which include: unscheduled smelter closures, geological and safety problems and a difficult industrial relations climate. This cut down the South African supplies by 4.9%–5.04 million ounces. In addition, the power supply crisis and flooding in early 2008 affected production of period.[21] In 2015, a short, mildly explosive episode was detected from November 15 to December 27. This could be ascribed to a stronger demand and tighter emissions restrictions in Europe.[22] This factor led to increase demand for platinum used in catalytic converters.

The empirical results detected a short, mildly explosive episode in the price of copper from January 25 to April 18, 2004 (Table 7b). Correspondingly, two other bubble episodes were detected: from April 23 to June 4, 2006 and between November 9, 2008 and January 4, 2009. The occurrence of explosive episode in the price of copper during the 2000s could be attributed solely to extraordinary growth in China's demand, as it dominates the global demand for copper.[23] Urbanisation, rural electrification and growing car and appliance ownership resulted in growing consumption. In the 2000s, China built thousands of a typical eight-storey building which requires the use of about 20 tons of copper wire and pipes. As the world shifts towards individual solar power units, the high tension voltage power lines (mostly aluminum) needed to be replaced for more of copper with lower voltages. Also, about 1500 new cars, each containing 50lbs of copper, were hitting China's roads each day. Millions of cell phones and PCs were produced in China, each containing ½oz and 1.5lbs of copper, respectively.[24] Besides, copper being the best non-precious metal conductor of electricity is mostly used in power cables, generators, motors and transformers. It is also used widely in the manufacture of electronics and electrical components.[25]

The price of silver also experienced two short, mildly explosive episodes: the first from March 14 to April 11, 2004, while the second spanned from May 7 to 14, 2006. Increased price of silver especially in 2006, can be explained by its outperforming over other commodity counterparts (likes gold and platinum). During this period, its demand grows at a rate of 58% and much of this demand is attributable to the launch of Silver Exchange Traded Funds (ETFs) by Barclays. The upward trend continued in 2007 with increased desire of investors for silver and strong industrial demand. This therefore implies that large investors have the power to influence market prices.[26]

5. Summary of findings, conclusion and recommendations

This study examines the major properties of prices of metals (gold, silver, platinum, palladium and copper) such as structural breaks, non-linearity, stationarity, and bubble incidences during 1990–2021. For robustness of results, both daily and weekly data sets were used, while two conventional unit root tests and two recent stationarity tests (including a new one) that account for structural breaks and non-linearity were also employed. The recently introduced method of identifying and detecting price bubble was also used.

The empirical findings of this study are very informative and useful.

[15] See Dey (2016).
[16] https://www.forbes.com/sites/naeemaslam/2020/06/25/gold-prices-trump-and-covid-19/?sh=2d92de582df1.
[17] www.platinum.matthey.com/prices/price_charts.html.
[18] See Johnson Matthey (2008).
[19] See Johnson Matthey (2008).
[20] https://www.usmoneyreserve.com/video-library/videos/why-is-the-price-of-palladium-skyrocketing/.
[21] See Johnson Matthey (2008).
[22] https://www.bbc.com/news/business-51171391.
[23] See van Gerwe (2016).
[24] https://www.winton.com/longer-view/copper-bottomed-booms-and-busts.
[25] https://www.investopedia.com/ask/answers/021715/what-factors-affect-price-copper.asp.
[26] https://tejas.iimb.ac.in/articles/80.php.

Table 7a
Data stamping of crisis and bubbles in Gold, Palladium and Platinum prices (Weekly data).

Gold			Palladium			Platinum		
Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration
1997-01-19	1997-02-16	5	1993-07-04	1993-07-04	1	2006-05-14	2006-05-28	3
1997-07-06	1997-08-24	8	1997-06-08	1997-06-08	1	2008-02-17	2008-03-16	5
1997-09-07	1997-09-21	3	1998-04-26	1998-04-26	1	2008-10-19	2008-11-02	3
1997-10-26	1998-01-25	14	1998-05-17	1998-05-17	1	2008-11-23	2008-11-23	1
1998-03-08	1998-03-22	3	2001-10-07	2001-11-25	8	2008-12-07	2008-12-07	1
1998-08-30	1998-08-30	1	2002-12-01	2003-01-05	6	2015-07-19	2015-08-09	4
1999-06-13	1999-06-27	3	2003-03-16	2003-06-29	16	2015-09-27	2015-10-04	2
1999-07-11	1999-08-08	5	2003-07-13	2003-07-27	3	2015-11-15	2015-12-27	7
1999-08-22	1999-09-19	5	2008-03-02	2008-03-02	1	2016-01-17	2016-01-24	2
2006-01-22	2006-01-22	1	2008-09-14	2008-10-26	7			
2006-02-05	2006-02-05	1	2008-12-07	2008-12-14	2			
2006-04-23	2006-05-21	5	2015-08-30	2015-09-06	2			
2013-06-30	2013-07-07	2	2016-01-10	2016-01-17	2			
2020-02-23	2020-02-23	1						
2020-03-08	2020-03-08	1						
2020-07-26	2020-08-16	4						
2020-08-30	2020-08-30	1						

Source: Computed by the Authors.

Table 7b
Data stamping of crisis and bubbles in Copper and Silver prices (Weekly data)

Copper			Silver		
Exuberance date	Collapse date	duration	Exuberance date	Collapse date	Duration
1993-05-09	1993-05-09	1	2004-03-14	2004-04-11	5
2004-01-11	2004-01-11	1	2006-05-07	2006-05-14	2
2004-01-25	2004-04-18	13	2013-06-23	2013-07-07	3
2006-04-23	2006-06-04	7			
2006-07-09	2006-07-16	2			
2008-10-26	2008-10-26	1			
2008-11-09	2009-01-04	9			
2015-01-25	2015-02-01	2			
2015-11-22	2015-12-06	3			
2016-01-10	2016-01-24	3			
2016-02-14	2016-02-14	1			

Source: Computed by the Authors.

Preliminary tests show that prices of the metals exhibit structural breaks and non-linearity. Both traditional unit root test (ADF and PP unit root tests) revealed that prices of all the metals are not stationary I(1). The application of Christopoulos and Leon-Ledesma (2010) and Guris (2018) tests produced stationary results I(0) except Silver, using weekly data set. However, although both tests performed well with daily data, Guris (2018) new test performed better than the C-L (2010) test when considering weekly data especially for all metals except Silver. Some incidences of bubble in prices of the metals were also detected and analysed.

A number of policy recommendations that are useful for investors, portfolio managers, producers, consumers, traders, analysts and policy makers can be deduced from the empirical results. The metal markets stakeholders should note that the metals' prices are characterized by structural breaks and non-linear structure which distort the efficient functioning of the market irrespective of the market conditions (crisis or non-crisis). However, since the empirical results reveal that when they are accounted for the equilibrium in the metal markets are restored, thus, these features of the metals prices are inherent market processes which may not be taken so serious by investors, policy makers and analysts as they constitute temporary shocks to the efficient functioning of the market. These potential sources of shocks in the metal markets can be categorized into market level shocks (such as changes in the market operation size and geographical location as well as in products features), country level shocks (including changes in government policy and structure) and global level shocks (such as global production and consumption imbalances, advancements in technology and innovation waves, knowledge and information). Similarly, the results suggest that the heterogeneous interactions and beliefs of the market participants, market frictions and transaction costs which constitute shocks to the metal markets functioning may not have permanent effect on prices. This is good for the resource dependent (metal) economy as efficiency of the resource market may influence the efficiency of the entire economy via inter-sectoral (especially financial and real sectors) and macroeconomic linkages.

The empirical findings in this study could aid revenue forecasting, risk management and formulating of policies relating to metals, particularly for revenue forecasting and risk management. The implication of the findings of this study is that the metals' markets are efficient and thus, it may not be easy for participants such as arbitrageurs and speculators to make the most of opportunities in the markets for abnormal returns. Further, the metals considered could be taken as pretty and fine hedging instruments in the interim. Moreover, investment expansion in these metals in the long term may be difficult if price related policies are employed since any reaction engendered by such policies will turn out short-term effect as there is high probability for prices of the metals to come back to long-run course.

Finally, in order to circumvent bogus findings that result into improper policy directions, research and policy analysts should consider the issues of structural break and non-linearity in econometrics modelling of the analysed metals.

CRediT authorship contribution statement

Bashir A. Wahab: Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Adeolu O. Adewuyi:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, critically for important intellectual content, Approval of the version of the manuscript to be published.

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APPENDIX A

Table 1
Test of Structural Breaks: Bai-Perron (2003) tests with multiple breakpoints

Daily data									
	No of breaks	TB	F(1)	F(2)	F(3)	F(4)	F(5)	UDmax	WDmax
Copper	5	11/20/2002, 8/15/2005, 1/15/2008, 7/01/2010, 11/17/2015	5999.846***	4179.649***	5165.040***	6501.071***	6875.917***	13751.83***	22259.78***
Gold	5	2/05/2003, 3/19/2008, 12/01/2010, 4/14/2015, 9/12/2017	4417.027***	9797.918***	13771.70***	14252.50***	15471.77***	30943.54***	50087.60***
Palladium	5	11/19/1997, 3/07/2001, 7/21/2009, 9/19/2014, 1/05/2018	11406.85***	9746.593***	9762.307***	9206.392***	9202.925***	22813.70***	29793.13***
Platinum	5	5/16/2001, 7/21/2006, 1/18/2008, 7/15/2010, 8/27/2014	7445.756***	7420.830***	8575.307***	9283.798***	10354.28***	20708.56***	33520.48***
Silver	5	1/22/2004, 2/05/2008, 6/28/2010, 3/26/2014, 10/10/2018	4706.348***	5438.303***	8355.192***	8591.172***	9582.149***	19164.30***	31020.81***
Weekly data									
Copper	5	6/08/2003, 4/16/2006, 10/12/2008, 5/01/2011, 11/13/2016	1229.67***	846.339***	1096.12***	1355.78***	1427.27***	2854.54***	4620.58***
Gold	5	7/06/2003, 10/19/2008, 8/07/2011, 2/07/2016, 8/05/2018	913.497***	2042.66***	2828.19***	2920.77***	3144.36***	6288.72***	10179.42***
Palladium	5	2/15/1998, 7/22/2001, 3/07/2010, 7/12/2015, 11/25/2018	2347.53***	2006.71***	1997.57***	1870.31***	1875.18***	4695.07***	6070.62***
Platinum	5	9/30/2001, 2/04/2007, 8/17/2008, 3/13/2011, 6/21/2015	1546.98***	1534.33***	1786.05***	1920.73***	2130.93***	4261.86***	6898.58***
Silver	5	7/11/2004, 9/07/2008, 2/27/2011, 1/11/2015, 9/22/2019	964.657***	1111.14***	1700.22***	1707.74***	1925.48***	3850.96***	6233.46***

Source: computed. Note: t indicates the t-statistic and TB denotes the structural break dates. The Bai-Perron tests of 1 to M globally determined breaks, the 1 per cent critical values for the F(1), F(2), F(3), F(4), F(5) test in the case of non-stationary variables are 15.37, 12.15, 10.27, 8.65 and 7.00 for $l = 1, 2, 3, 4, 5$, respectively. The critical value for the UDmax test is 15.41 while the critical value for the WDmax test is 17.01. *, ** and *** denote rejection of the null hypothesis of a unit root at 10 per cent, 5 per cent and 1 per cent significance levels.

Table 2a
Data stamping of crisis and bubbles in Gold, Palladium and Platinum prices (Daily data).

Gold			Palladium			Platinum		
Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration
1992-07-20	1992-07-20	1	1990-09-28	1990-09-28	1	1990-10-15	1990-10-18	4
1992-07-23	1992-07-23	1	1990-10-15	1990-10-17	3	1996-12-09	1996-12-10	2
1993-04-26	1993-04-27	2	1991-08-15	1991-08-16	2	1996-12-16	1996-12-17	2
1993-04-29	1993-05-10	7	1992-12-08	1992-12-08	1	1997-01-06	1997-01-09	4
1993-05-12	1993-06-01	14	1992-12-11	1992-12-15	3	1997-01-14	1997-01-27	10
1993-06-04	1993-06-04	1	1992-12-17	1992-12-18	2	1997-01-29	1997-02-11	10
1993-07-06	1993-07-14	7	1995-03-24	1995-03-24	1	1997-06-05	1997-06-09	3
1993-07-19	1993-07-19	1	1996-09-23	1996-09-24	2	1997-12-16	1997-12-16	1
1993-07-30	1993-08-04	4	1997-02-10	1997-02-14	5	1999-09-29	1999-09-29	1
1996-12-03	1996-12-03	1	1997-02-25	1997-03-04	6	1999-10-04	1999-10-04	1
1997-01-03	1997-02-20	35	1997-03-10	1997-03-11	2	1999-10-07	1999-10-14	6
1997-07-04	1997-07-17	10	1997-05-20	1997-05-20	1	1999-11-11	1999-11-11	1
1997-07-24	1997-07-24	1	1997-05-28	1997-05-29	2	2000-02-04	2000-02-17	10
1997-08-06	1997-08-06	1	1997-06-04	1997-06-12	7	2001-07-20	2001-07-24	3
1997-11-14	1997-11-18	3	1997-08-04	1997-08-05	2	2001-07-30	2001-08-22	18
1997-11-20	1997-11-20	1	1998-04-22	1998-04-24	3	2001-08-30	2001-09-04	4
1997-11-25	1998-01-20	38	2000-01-28	2000-03-22	39	2001-09-06	2001-09-06	1
1999-06-09	1999-06-18	8	2000-07-21	2000-07-21	1	2001-10-01	2001-10-02	2
1999-06-22	1999-06-22	1	2000-07-31	2000-08-02	3	2003-02-03	2003-02-05	3
1999-07-13	1999-07-13	1	2000-12-04	2000-12-05	2	2003-12-17	2003-12-17	1
1999-07-15	1999-07-15	1	2000-12-07	2000-12-28	13	2006-01-16	2006-01-16	1
1999-07-20	1999-07-20	1	2001-07-18	2001-08-02	12	2006-01-30	2006-02-06	6
1999-09-27	1999-10-15	15	2001-08-06	2001-08-09	4	2006-05-02	2006-05-31	21
2002-05-29	2002-05-29	1	2001-08-15	2001-08-16	2	2006-06-02	2006-06-05	2
2003-01-23	2003-02-07	12	2001-08-20	2001-08-20	1	2007-10-19	2007-10-19	1
2005-12-05	2005-12-05	1	2001-09-26	2001-10-12	13	2008-01-25	2008-03-18	38
2005-12-07	2005-12-13	5	2001-10-16	2001-10-26	9	2008-03-27	2008-03-27	1
2006-01-03	2006-01-04	2	2001-10-30	2001-11-01	3	2008-03-31	2008-03-31	1

(*continued on next page*)

Table 2a (*continued*)

Gold			Palladium			Platinum		
Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration	Exuberance date	Collapse date	duration
2006-01-06	2006-02-07	23	2001-11-13	2001-11-13	1	2008-08-12	2008-08-13	2
2006-02-09	2006-02-09	1	2002-11-25	2002-11-25	1	2008-08-15	2008-08-21	5
2006-04-06	2006-04-06	1	2002-12-04	2003-01-03	18	2008-09-02	2008-09-02	1
2006-04-10	2006-04-12	3	2003-03-24	2003-05-20	39	2008-09-05	2008-09-23	13
2006-04-18	2006-05-31	30	2003-05-22	2003-05-22	1	2008-09-25	2008-12-12	57
2007-10-17	2007-10-19	3	2004-04-13	2004-04-13	1	2008-12-16	2008-12-16	1
2007-10-26	2007-11-14	14	2004-12-17	2004-12-17	1	2011-09-29	2011-10-06	6
2007-11-23	2007-11-26	2	2005-11-10	2005-11-22	9	2011-12-29	2011-12-29	1
2008-01-03	2008-01-03	1	2005-11-24	2005-12-13	14	2013-06-26	2013-06-28	3
2008-01-07	2008-01-18	10	2006-02-03	2006-02-03	1	2014-10-01	2014-10-07	7
2008-01-23	2008-02-01	8	2006-05-11	2006-05-12	2	2014-10-10	2014-10-13	4
2008-02-08	2008-02-12	3	2007-08-22	2007-08-22	1	2014-10-15	2014-10-16	2
2008-02-19	2008-02-19	1	2008-02-11	2008-02-11	1	2014-10-31	2014-10-31	1
2008-02-21	2008-03-18	19	2008-02-18	2008-03-07	15	2014-11-05	2014-11-14	10
2009-11-18	2009-11-18	1	2008-08-12	2008-10-28	55	2015-03-17	2015-03-18	2
2009-11-23	2009-12-04	10	2008-10-31	2008-11-03	2	2015-07-08	2015-07-08	1
2011-08-09	2011-08-11	3	2008-11-20	2008-11-21	2	2015-07-13	2015-07-13	1
2011-08-16	2011-08-23	6	2008-12-01	2008-12-09	7	2015-07-15	2015-08-13	22
2011-09-02	2011-09-06	3	2008-12-12	2008-12-16	3	2015-08-17	2015-08-19	3
2013-04-15	2013-04-19	5	2011-10-03	2011-10-05	3	2015-08-24	2015-08-24	1
2013-04-23	2013-04-23	1	2015-07-08	2015-07-09	2	2015-08-26	2015-08-26	1
2013-05-17	2013-05-21	3	2015-07-16	2015-07-31	12	2015-09-11	2015-09-17	7
2013-06-20	2013-07-08	13	2015-08-04	2015-08-10	7	2015-09-22	2015-10-08	12
2014-11-05	2014-11-06	2	2015-08-18	2015-08-19	2	2015-11-09	2015-12-23	33
2016-12-01	2016-12-01	1	2015-08-24	2015-08-28	5	2015-12-30	2015-12-30	1
2016-12-05	2016-12-05	1	2016-01-07	2016-01-07	1	2016-01-06	2016-01-26	1
2016-12-12	2016-12-13	2	2016-01-11	2016-01-14	4	2016-01-29	2016-01-29	1
2016-12-15	2016-12-28	6	2016-01-20	2016-01-20	1	2016-02-02	2016-02-03	2
2018-08-14	2018-08-20	5	2019-01-17	2019-01-17	1	2018-07-02	2018-07-04	3
2019-06-25	2019-06-25	1	2019-02-20	2019-02-20	1	2018-07-18	2018-07-19	2
2019-08-07	2019-09-06	22	2019-02-25	2019-03-04	6	2018-08-15	2018-08-17	3
2020-02-24	2020-02-25	2	2019-03-19	2019-03-21	3	2020-03-16	2020-03-23	8
2020-02-27	2020-02-27	1	2020-01-15	2020-01-27	9			
2020-03-06	2020-03-09	4	2020-02-04	2020-02-06	3			
2020-07-23	2020-08-24	23	2020-02-14	2020-02-28	11			
2020-08-26	2020-08-26	1						
2020-08-28	2020-09-03	4						
2020-09-09	2020-09-16	6		Source: Authors 'computations				

Table 2b
Data stamping of crisis and bubbles in Silver and Copper prices (Daily data).

Silver			Copper		
Exuberance date	Collapse date	Duration	Exuberance date	Collapse date	Duration
1990-10-12	1990-10-12	1	1992-07-07	1992-07-08	2
1990-10-16	1990-10-16	1	1992-07-10	1992-07-10	1
1990-10-29	1990-10-29	1	1992-07-14	1992-07-24	9
1991-02-25	1991-02-25	1	1993-04-16	1993-04-16	1
1993-04-29	1993-04-29	1	1993-04-20	1993-04-22	3
1993-05-13	1993-05-13	1	1993-05-04	1993-05-11	6
1993-05-19	1993-05-19	1	1993-05-14	1993-05-17	2
1993-05-24	1993-05-24	1	1994-05-23	1994-05-23	1
1994-12-06	1994-12-06	1	1994-06-13	1994-06-13	1
1994-12-08	1994-12-08	1	1994-06-17	1994-06-17	1
1998-02-05	1998-02-06	2	1997-12-16	1997-12-16	1
2004-01-12	2004-01-14	3	1997-12-29	1997-12-30	2
2004-03-22	2004-03-24	3	1998-01-02	1998-01-12	7
2004-03-29	2004-04-13	10	2001-11-07	2001-11-07	1
2005-12-09	2005-12-12	2	2004-01-05	2004-01-05	1
2006-03-30	2006-04-20	14	2004-01-08	2004-01-09	2
2006-04-24	2006-05-12	14	2004-01-14	2004-01-14	1
2006-05-17	2006-05-17	1	2004-01-20	2004-04-20	64
2008-03-06	2008-03-06	1	2006-04-18	2006-04-28	9
2008-09-10	2008-09-17	6	2007-01-04	2007-01-09	4
2008-10-17	2008-10-17	1	2007-01-18	2007-01-18	1
2008-10-23	2008-10-28	4	2008-10-01	2008-10-28	20
2010-11-09	2010-11-11	3	2008-10-30	2009-01-05	45
2010-12-07	2010-12-07	1	2009-01-07	2009-01-08	2
2013-04-15	2013-04-18	4	2009-01-12	2009-01-12	1
2013-04-23	2013-04-24	2	2009-01-14	2009-01-15	2

(*continued on next page*)

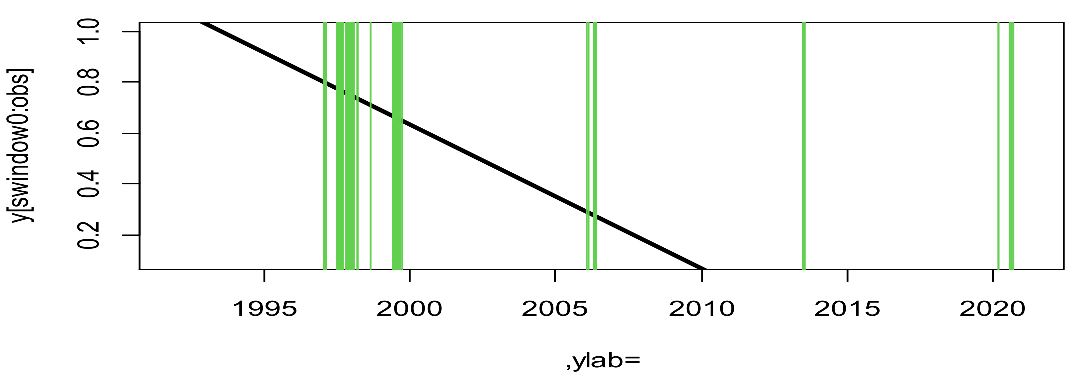
Table 2b (*continued*)

Silver			Copper		
Exuberance date	Collapse date	Duration	Exuberance date	Collapse date	Duration
2013-05-16	2013-05-16	1	2009-01-21	2009-01-22	2
2013-05-20	2013-05-20	1	2011-09-23	2011-09-26	2
2013-06-20	2013-07-10	15	2011-09-28	2011-10-05	6
2013-07-12	2013-07-12	1	2011-10-20	2011-10-20	1
2013-07-18	2013-07-19	2	2013-04-19	2013-04-23	3
2014-10-31	2014-11-14	11	2015-01-14	2015-01-15	2
2018-09-04	2018-09-05	2	2015-01-23	2015-02-02	7
2018-09-07	2018-09-07	1	2016-11-09	2016-11-15	5
2018-09-11	2018-09-11	1	2016-11-21	2016-12-01	8
2019-08-28	2019-09-05	7	2016-12-05	2016-12-06	2
2020-03-16	2020-03-23	8	2017-08-28	2017-08-29	2
			2017-09-01	2017-09-07	4
			2018-07-19	2018-07-19	1
			2018-08-15	2018-08-15	1
			2020-03-16	2020-03-30	11
			2020-04-01	2020-04-01	1
			2021-02-24	2021-02-25	2

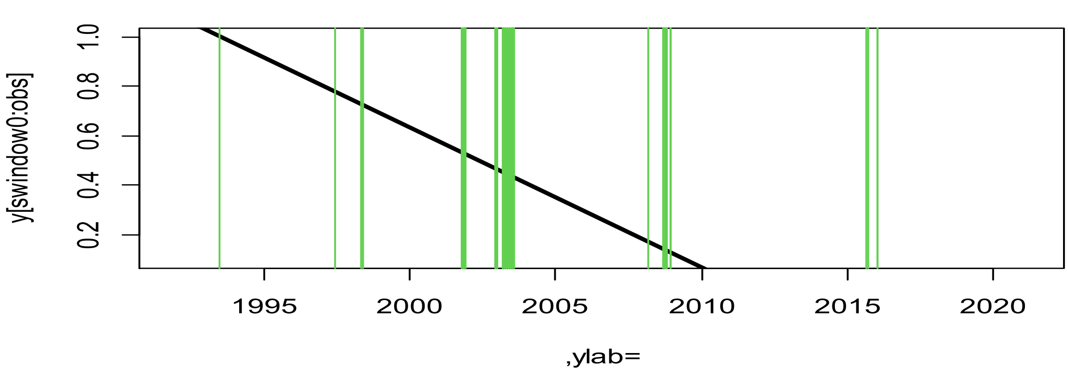
Source: Computed by the Authors.
Note: the total observations for the daily series is over 8000 and it is larger than what the software can run. For ease of analysis, these observations were therefore disaggregated based on the periods, such as 1990–2000, 2001–2010, and 2011–2021, respectively. Then, the bubbles and crisis periods were systematically and sequentially arranged following the dates.

APPEDIX B

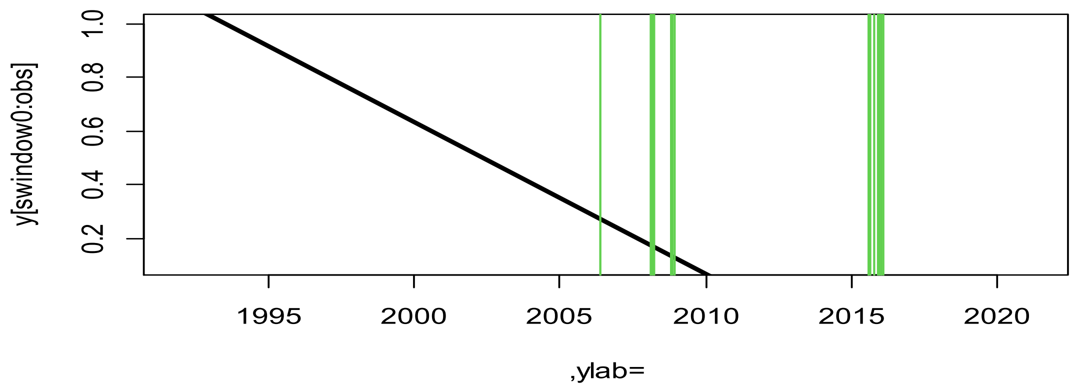
Gold



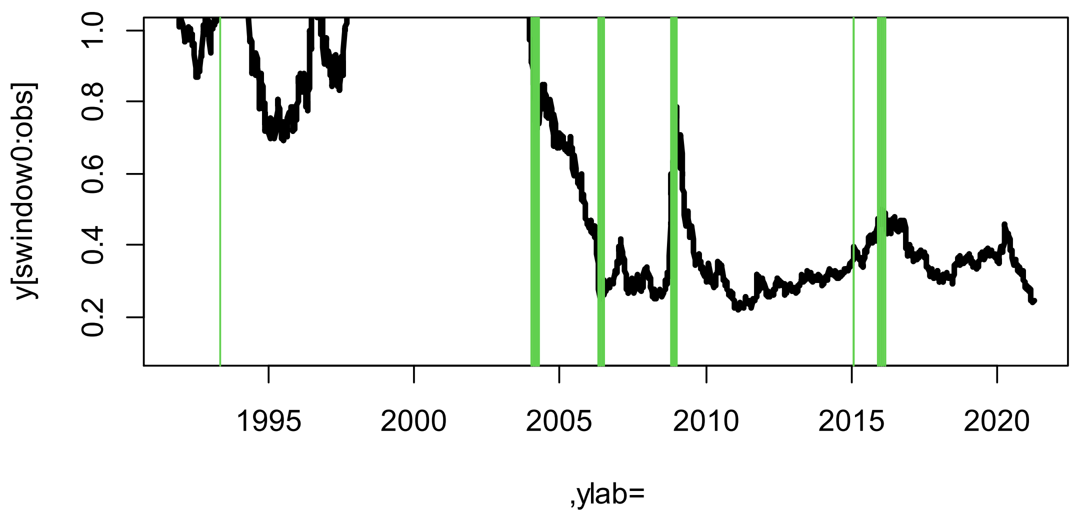
Palladium



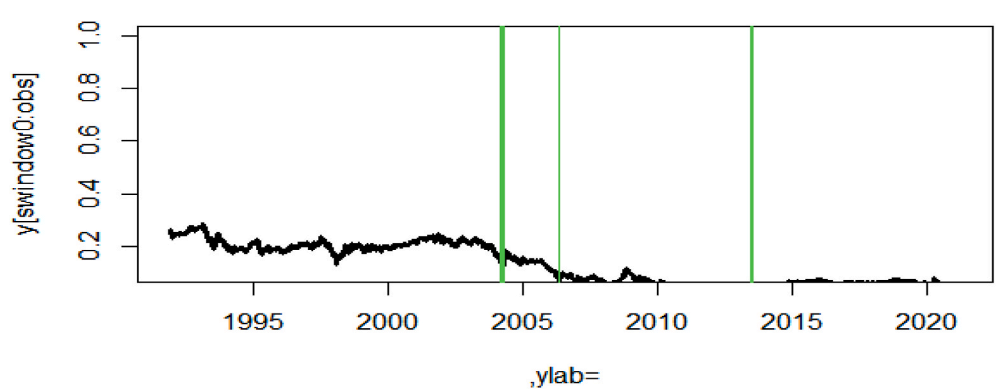
Platinum



Copper



Silver



References

Adewuyi, A.O., Wahab, B.A., Adeboye, O.S., 2020. Stationarity of prices of precious and industrial metals using recent unit root methods: implications for markets' efficiency. Resour. Pol. 65, 101560.

Arouri, M.E.H., Hammoudeh, S., Amine, L., Nguyen, D.K., 2012. Long memory and structural breaks in modelling the return and volatility dynamics of precious metals. Q. Rev. Econ. Finance 52 (2), 207–218.

Arouri, M.E.H., Hammoudeh, S., Amine, L., Nguyen, D.K., 2013. On the short- and long-run efficiency of energy and precious, metal markets. Energy Econ. 40, 832–844.

Bai, J., Perron, P., 1998. Estimating and testing linear models with multiple structural changes. Econometrica 66, 47–78.

Bai, J., Perron, P., 2003. Computation and analysis of multiple structural change models. J. Appl. Econom. 18 (1), 1–22.

Bayraktar, A., 2012. Etkin piyasalar hipotezi, T. C. *Aksaray Üniversitesi İ.İ.B.F.* Dergisi 3 (1), 37–46.

Becker, R., Enders, W., Hurn, S., 2004. A general test for time dependence in parameters. J. Appl. Econom. 19, 899–906.

Becker, R., Enders, W., Lee, J., 2006. A stationarity test in the presence of unknown number of smooth breaks. J. Time Anal. 27, 381–409.

Bouri, E., Chang, T., Gupta, R., 2017. Testing the efficiency of the wine market using unit root tests with sharp and smooth breaks. Wine Economics and Policy 6, 80–87.

Campbell, J.Y., Lo, A.W., MacKinlay, A.C., 1998. The Econometrics of Financial Markets. Princeton University Press, New Jersey.

Charles, A., Darné, O., Kim, J.H., 2015. Will precious metals shine? A market efficiency perspective. In: International Review of Financial Analysis, vol. 41. Elsevier, pp. 284–291. https://doi.org/10.1016/j.irfa.2015.01.018.

Cheung, Y.-W., Lai, K.S., 1993. Do gold market returns have long memory? Financ. Rev. 28 (2), 181–202.

Christopoulos, D.K., Leon-Ledesma, M.A., 2010. Smooth breaks and non-linear mean reversion: post-Bretton Woods real exchange rates. J. Int. Money Finance 29, 1076–1093.

Dickey, D.A., Fuller, W.A., 1979. Distribution of the estimators for autoregressive time series with a unit root. J. Am. Stat. Assoc. 74, 427–431.

Enders, W., Lee, J., 2004. Testing for a Unit Root with a Nonlinear Fourier Function. University of Alabama, Mimeo.

Fama, E.F., 1965. The behavior of stock market prices. J. Bus. 38, 34–105.

Fama, E.F., 1970. Efficient capital markets: a review of theory and empirical work. J. Finance 25 (2), 383–417.

Figuerola-Ferretti, I., Gilbert, C.L., 2008. Commonality in the LME aluminum and copper volatility processes through a FIGARCH lens. J. Futures Mark. 28 (10), 935–962.

Gharib, Cheima, Mefteh-Wali, Salma, Ben Jabeur, Sami, 2020. Finance research letters. https://doi.org/10.1016/j.frl.2020.101703.

Gil-Alana, L.A., Tripathy, T., 2014. Modelling volatility persistence and asymmetry: a Study on selected Indian non-ferrous metals markets. Resour. Pol. 41, 31–39.

Gil-Alana, L.A., Chang, S., Balcilar, M., Aye, C.G., Gupta, R., 2015. Persistence of precious metal prices: a fractional integration approach with structural breaks. Resour. Policy. 44, 57–67.

Güriş, B., 2018. A new nonlinear unit root test with fourier function. Commun. Stat. Simulat. Comput. 1532–4141.

Harvey, D.I., Leybourne, S.J., 2007. Testing for time series linearity. Econom. J. 10, 149–165.

Harvey, D.I., Leybourne, S.J., Xiao, B., 2008. "A powerful test for linearity when the order of integration is unknown" studies nonlinear dynamics. Econ. Times 21 (3), 2.

Harvey, D.I., Leybourne, S.J., Sollis, R., Taylor, A.M.R., 2014. Tests for explosive financial bubbles in the presence of nonstationary volatility. In: A Paper Presented at the Conference on Recent Developments in Financial Econometrics and Empirical Finance. held at the University of Essex on June, 12th and 13th 2014.

Hasanov, M., Omay, T., 2007. Are the transition stock markets efficient? Evidence from non-linear unit root tests. Central Bank Review 27, 1–12. http://www.tcmb.gov.tr/research/review/.

Kapetanios, G., Shin, Y., Snell, A., 2003. Testing for a unit root in the nonlinear STAR framework. J. Econom. 112, 359–379.

Kenourgios, D., Samitas, A., 2004. Testing efficiency of the copper futures market: new evidence from London Metal Exchange. Global Bus. Econ. Rev. 261–271.

Khan, K., Köseoğlu, S.D., 2020. Is palladium price in bubble? Resour. Pol. 68, 101780. https://doi.org/10.1016/j.resourpol.2020.101780.

Kruse, R., 2011. A new unit root test against ESTAR based on a class of modified statistics. Stat. Pap. 52 (1), 71–85.

Kwiatkowski, D., Phillips, P.C.B., Schmidt, P., Shin, Y., 1992. Testing the null-hypothesis of stationarity against the alternative of a unit root: how sure are we that economic time series have a unit root? J. Econom. 54, 159–178.

Lind, H., 2009. Price bubbles in housing markets: concept, theory and indicators. Int. J. Housing Market. Anal. 2 (1), 78–90.

Liu, R., Narayan, P.K., 2010. A new structural break unit root test based on a GARCH model; (as referenced in Narayan, P.K and Liu, R. Are shocks to commodity prices persistent? Appl. Energy 88 (2011), 409–416.

Lucey, B.M., O'Connor, F.A., 2013. Do bubbles occur in the gold price? An investigation of gold lease rates and Markov switching models. *Borsa Istanbul Review*vol 13, 53–63.

Ludlow, J., Enders, W., 2000. Estimating non-linear ARMA models using Fourier coefficients. Int. J. Forecast. 16 (3), 333–347.

Mensi, W., Sensoy, A., Vod, X.V., Kange, S.H., 2020. Impact of COVID-19 outbreak on asymmetric multifractality of gold and oil prices. Resour. Pol. 69, 101829.

Narayan, P.K., Liu, R., 2011. Are shocks to commodity prices persistent? Appl. Energy 88, 409–416.

Narayan, P.K., Popp, S., 2010. A new unit root test with two structural breaks in level and slope at unknown time. J. Appl. Stat. 37 (9), 1425–1438.

Narayan, P.K., Narayan, S., Popp, S., 2010. Energy consumption at the state level: the unit root null hypothesis from Australia. Appl. Energy 87, 1953–1962.

Ntim, C.G., English, J., Nwachukwu, J., Wang, Y., 2015. On the efficiency of the global gold markets. Int. Rev. Financ. Anal. 41, 218–236. https://doi.org/10.1016/j.irfa.2015.03.013.

Otto, S., 2010. Does the London Metal Exchange follow a random walk? Evidence from the predictability of futures prices. Open Econ. J. 3, 25–41. https://doi.org/10.2174/1874919401003010025.

Phillips, P.C.B., Shi, S., 2018. Financial bubble implosion and reverse regression. Econom. Theory 34 (4), 705–753.

Phillips, P.C., Shi, S., 2020. Real time monitoring of asset markets: Bubbles and crises. In: Handbook of Statistics (Vol. 42, pp. 61-80). Elsevier.

Phillips, P.C.B., Wu, Y., Yu, J., 2011. Explosive Behavior in the 1990s NASDAQ: when Did Exuberance Escalate: A Collapse in the S&P 500. Singapore Management University Working. Paper No. 04-2013.

Pindyck, R., 1993. The present value model of rational commodity pricing. Econ. J. 103 (418).

Shafiee, S., Topal, E., 2010. An overview of global market and gold price forecasting. Res. Pol. 35, 178–189.

Solarin, S.A., Lean, H.H., 2016. Are fluctuations in oil consumption permanent or transitory? Evidence from linear and nonlinear unit root tests. Energy Policy 88, 262–270.

Su, C.-W., Wang, K.H., Chang, H.-L., Dumitrescu–Peculea, A., 2017. Do iron ore price bubbles occur? Resour. Pol. 53, 340–346.

Su, C.-W., Wang, X.-Q., Zhu, H., Tao, R., Moldovan, N.-C., Lobonţ, O.-R., 2020. Testing for multiple bubbles in the copper price: periodically collapsing behavior. Resour. Pol. 65, 101587.

Tapia, C., Coulton, J., Saydam, S., 2020. Using entropy to assess dynamic behaviour of long-term copper price. Resour. Pol. 66, 101597. https://doi.org/10.1016/j.resourpol.2020.101597.

Uludag, B.K., Zorikto Lkhamazhapov, Z., 2014. Long memory and structural breaks in the returns and volatility of gold:evidence from Turkey. Appl. Econ. 46 (1), 3777–3787.

Wang, D., Tomek, W.G., 2007. Commodity prices and unit root tests. Am. J. Agric. Econ. 89 (4), 873–889.

Worthington, A.C., Higgs, H., 2003. Weak-form Market Efficiency in European Emerging and Developed Stock Markets (Discussion Paper No 159). School of Economics and Finance. Queensland University of Technology, Australia.

Yıldırım, D.C., Cevik, E.I., Esen, O., 2020. Time-varying volatility spillovers between oil prices and precious metal prices. Resour. Pol. 68, 101783. https://doi.org/10.1016/j.resourpol.2020.101783.

Zhang, B., Li, X., He, F., 2014. Testing the evolution of crude oil market efficiency: data have the conn. Energy Pol. 68, 9–52. https://doi.org/10.1016/j.enpol.2013.12.052i.

Zhao, Y., Chang, H.L., Su, C.W., Nian, R., 2015. Gold bubbles: when are they most likely to occur? Jpn. World Econ.