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Stochastic structure of metal prices: Evidence from fractional integration non-linearities and breaks

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ABSTRACT

This paper investigates the long memory properties of the prices series of two major precious metals (gold and silver) and six non-precious metals (aluminium, copper, lead, zinc, tin and nickel) by using a fractional integration modelling framework, while controlling for structural breaks and non-linearities. We use daily data in a range from November 01, 2007 to March 20, 2020. From the results, Copper and Tin exhibit a very small degree of mean reversion. However, if autocorrelation is permitted, the unit root null hypothesis cannot be rejected in any of the series. We also account for structural breaks and non-linearities. We observe that all the series under investigation are exposed to multiple breaks. Results obtained under white noise errors shows some evidence of mean reversion for silver aluminium, copper, tin and zinc in some of the subsamples. However, under the assumption of Bloomfield autocorrelated errors the confidence intervals are so wide that we cannot confirm this evidence in any single case.

1. Introduction

In recent decades, precious metals such as gold has emerged as an important asset class among portfolio investors and the broader economy (Baur and Lucey, 2010). It is noteworthy to mention that both precious and non-precious metals have attracted academic attention leading to a comprehensive literature with majority of studies examining the relationship between metals and other asset classes (stocks, bonds, exchange rates, commodities, etc.) to ascertain the diversification potential of metals. (e.g., Shahzad et al., 2019; Baur and Lucey, 2010; Coudert and Raymond, 2011; Narayan and Narayan, 2010; Kang et al., 2017; Rehman, 2018; etc.). Baur and Lucey (2010) reveal that precious metals offers valuable diversification opportunities to investors and serves as a monetary medium when the market is uncertain, as well as having a wide range of manufacturing and industrial applications (e.g., Arouri et al., 2012; Batten et al., 2010; Christie–David et al., 2000; Ciner, 2001). Other studies examine the relationship between precious and non-precious metals. For example, Batten et al. (2013) examine the dynamics of the bivariate relationship between gold and silver prices and find a positive dependence in the gold-silver spread returns which suggests the series will not immediately revert to its average or long-term mean therefore offering traders limited profit opportunities.

Given the emergence of metals as an investment assets class in recent years (Beckmann et al., 2019; Baumöhl and Lyócsa, 2017), the price dynamics and characteristics of precious and non-precious metals have long been a matter of popular concern (Gil-Alana et al., 2015). For instance, following the monotonic behaviour of metal prices from the late 1990s to 2008, a number of studies have successfully modelled the stochastic nature of precious and non-precious metals. Cochran, Mansur and Odusami (2012) find long-memory properties in the returns and return volatilities of copper, gold, platinum and silver. According to them, they are influenced by a common risk factor and failure to explicitly model this factor will yield less than optimal portfolio diversification. Baur (2013) analyzed gold returns for each month from 1980 to 2010 and found that September and November are the only months with positive and statistically significant gold price changes. Interestingly, little is known about statistical properties of both precious and non-precious metals even though a considerable number of studies have dealt with commodity price dynamics and have shown significant volatility clustering and long-persistence of commodity price returns. (Agnolucci, 2009; Akram, 2009 etc.). Our paper extends the literature by investigating the stochastic properties of metal prices under structural breaks and nonlinearities. Notable studies close to our paper include studies by Gil-Alana et al. (2015), Arouri et al. (2012) and Ewing

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and Malik (2013) who examined persistence of precisions metals. In our study, we study the persistence of both precious and non-precious metals using a robust estimation technique while accounting for the effect of structural breaks and non-linearities in the data generating process of financial and macroeconomic variables.

Financial and macroeconomic variables are known to exhibit some statistical properties that might have implications for investors, policy makers, producers, researcher, consumers and portfolio investors. Two of these characteristics including persistence and structural breaks have received considerable attention (Stock and Watson, 1996; Gil-Alana et al., 2020, 2021 ; Abakah and Gil-Alana, 2022). Modelling the degree of persistence to measure the extent to which current short-term shocks lead to permanent future changes is important since it reflects the stability of the financial and macroeconomic variable of the relevant country (Alexander and Barrow, 1994). Thus, a better understanding of past trends is needed to improve our ability to predict future changes in metal prices. In addition, persistence of metal price shocks can be transmitted to other sectors of the economy where such shocks could be transitory or persistent. Literature suggest that persistence can be estimated using unit root tests (e.g., Phillips, 1987; Phillips and Perron, 1988; Lee and Strazicich, 2003, 2004). However, the use of unit roots are limited by several caveats given that units roots have low power in the case of high persistence (Spanos, 1990; Caporale and Pittis, 1999) which results in the over-acceptance of the null hypothesis. Additionally, a second limitation of the unit root tests is that it test persistence without accounting for structural breaks, which can result in overestimation of persistence. Lee et al. (2006) find that structural breaks are important in examining the persistence of commodity price returns dynamics. In the present study, the goal is to extend the literature by examining the stochastic structure and the properties of two precious metals (gold and silver) and six non-precious metals (aluminium, copper, lead, zinc, tin and nickel) using fractional integration techniques while accounting for structural breaks and nonlinearities following the recent movements in metal prices and emergence of metals as an enviable asset class.

We make several contributions in this paper. First, following the drawbacks and limitations associated with unit root tests used mostly by earlier studies to examine the structure of metal returns, we contribute to the literature by using updated techniques based on the concepts of fractional integration using recent data of metal returns under-structural breaks. This method might be more appropriate than the standard ones given that they allow for a much greater degree of flexibility in their dynamic specification, allowing for fractional degrees of differentiation since it is a well acknowledged fact that return distributions are nonnormal. Modified versions of fractional integration have been used by a number of empirical studies investigating the dynamics of financial prices, including Gil-Alana et al. (2018, 2020) among others, and so we add to this literature. Moreover, Abakah et al. (2018) using a non-linear approach to study the random walk theory in selected African markets note that accounting for unknown structural breaks and non-linearity in the data generating process of financial prices yields better approximations. Hence, in this paper, we account for unknown structural breaks in the series of metal returns. Secondly, most studies in the past have ignored non-precious metals (Batten et al., 2013; Tweneboah, 2019; Tweneboah and Alagidede, 2018; Baur, 2013, Cochran et al., 2012), however in this study, we throw more insights on the price dynamics of both precious and non-precious metals.

We document several interesting findings. Copper and Tin exhibit a very small degree of mean reversion. However, if autocorrelation is permitted, the unit root null hypothesis cannot be rejected in any of the series. We also account for structural breaks and non-linearities. We observe that all the series under investigation are exposed to multiple breaks. Results obtained under white noise errors show some evidence of mean reversion for silver aluminium, copper, tin and zinc in some of the subsamples. The remainder of the paper is organized as follows. In Section 2, a brief literature review is given on the modelling of commodity return volatility from a methodological stand point. Section 3 presents the methodology. Section 4 describes the data. Discussion of the empirical results is provided in Section 5, followed by conclusions in Section 6.

2. Structure of metal returns: a methodological note

Although the empirical investigation of the price dynamics of various financial and economic variables and their practical implications has been receiving attention in the fields of financial and macroeconomic analyses, not much has been done within the metals market space. From a methodological stand point, the few studies that examined the price dynamics of metals have used varied econometric approaches as reported in Table 1.

3. Methodology

This section briefly describes the fractional integration approach employed in the empirical work carried out in Section 5. Fractional integration means that a series may display a fractional order of integration. This is very flexible since it allows for a higher degree of generality compared with the classical cases that simply consider 0 as the order of integration for stationary series, and 1 for nonstationary ones.

A series $\{x_t, t = 1, 2, \ldots\}$is said to be integrated of order d ($x_t \approx I(d)$) if it can be expressed as:

$$(1 - B)^d x_t = u_t, \quad t = 1, 2, \ldots, \tag{1}$$

where B is the backshift operator, i.e., $Bx_t = x_{t-1}$, and u_t is I(0). We say that x_t displays the property of long memory if $d > 0$, and if $0 < d < 0.5$, x_t is covariance stationary though with the autocorrelations decaying much more smaller than in the AR case; if $0.5 = d < 1$, x_t is no longer second order stationary but the series is still mean reverting with shocks

Table 1
Methodological literature on structure and price dynamics of metal returns.

No	Author(s)	Methodology	Variables
1	Figuerola-Ferretti and Gonzalo (2010)	Cointegration techniques of Johansen (1991)	Commodities including metals
2	Batten et al. (2013)	Hurst coefficient (Hurst, 1951)	Gold and Silver
3	Cochran et al. (2012)	Fractional Integration GARCH (FIGARCH)	Metals
4	Tweneboah and Alagidede (2018)	Wavelet multiple correlations and cross-correlations	Precious metals
5	Gil-Alana and Tripathy (2014)	Fractional integration	Non-ferrous metals
6	Sari et al. (2010)	Generalized forecast error variance decomposition and the generalized impulse response functions of Koop et al. (1996) and Pesaran and Shin (1998)	Precious metals
7	Cheung and Lai (1993)	New rescaled range technique	Gold
8	Arouri et al. (2012)	Parametric and semiparametric methods including the ARFIMA-FIGARCH model	Precious metals including gold, silver, platinum and palladium.
9	Uludag and Lkhamazhapov (2014)	Parametric and semiparametric methods including the ARFIMA-FIGARCH model	Gold futures
10	Ewing and Malik (2013)	GARCH model	Gold
11	Gil- Alana et al. (2015)	Fractional integration	Precious metal including gold, silver, rhodium, palladium and platinum

having temporary though long lasting effects.

The estimation of the differencing parameter d will be based on the Whittle function expressed in the frequency domain, following the testing approach developed by Robinson (1994) which is very convenient in the context of nonstationary data as is used in this work.

The estimation of the differencing parameter d will be based on the Whittle function expressed in the frequency domain, following the testing approach developed by Robinson (1994) which is very convenient in the context of nonstationary data as is used in this work. In Robinson (1994) the model examined is the following one

$$(1 - B)^{d_1}(1 + B)^{d_2}\prod_{j=3}^{3}(1 - 2\cos w_r B + B^2)^{d_j} x_t = u_t, \quad t = 1, 2, \ldots, \tag{2}$$

where $d = (d_1, d_2, \ldots, d_n)^T$ are parameters to be tested under the null hypothesis

$$H_o : d = d_o, \tag{3}$$

with $d_o = (d_{1o}, d_{2o}, \ldots, d_{no})^T$. Robinson (1994) showed that under H_o (3), the test statistic (say R), follows aysmptocially a χ^2_n- distribution.

In our case, we impose $d_j = 0$ for $j \geq 2$, (2) becomes (1) and thus, $n = 1$, and the limit distribution is standard normal. Moreover, this distribution holds independently of the inclusion of deterministic terms in the model such that x_t in (1) can be, for example, the errors in a regression model with an intercept and a linear time trend and is also unaffected by potential autocorrelation in the disturbances u_t. A full description of this version of Robinson's (1994) tests can be found in Gil-Alana and Robinson (1997) and recent applications including this approach are among others Gil-Alana et al. (2018), Apergis and Carmona (2020) and Sakiru et al. (2021).

4. Data

Our dataset obtained from DataStream contains times series of precious and non-precious spot-prices, with daily frequency, for a sample of two precious metals (Gold and Silver) and five non-precious metals (Aluminium, Copper, Lead, Zinc, Tin and Nickel). Our sample period ranges from November 01, 2007 to March 20, 2020 with varying starting dates across the series. Table 2 presents the summary statistics and reveals that over the time span chosen for the study among the eight metals there has been maximum fluctuation in the price of zinc followed by gold and silver. The distribution for all series is left skewed, where copper is at the higher end of these spectrums.

5. Empirical analysis

Following Gil-Alana and Hualde (2009), Gil-Alana and Moreno (2012) and other applied papers on fractional integration with the tests of Robinson (1994), we considering the following model,

$$y_t = \beta_0 + \beta_1 t + x_t; \quad (1 - L)^d x_t = u_t, \quad t = 0, 1, \ldots, \tag{4}$$

where y_t refers to each of the observed time series (precious and non-precious metals prices, in logs); β_0 and β_1 are unknown coefficients referring, respectively, to a constant and a linear time trend, while x_t is supposed to be I(d), where d is a parameter to be estimated from the data.

Tables 3 and 4 display the results under the assumption that u_t is uncorrelated, while in Tables 5 and 6 we suppose u_t is autocorrelated, using here the exponential spectral approach of Bloomfield (1973). Across Tables 3 and 5 we display the estimates of d (and the 95% confidence bands) for three different modelling set-ups: 1) with no terms in (2), i.e., imposing a priori that β_0 and β_1 are equal to zero; 2) with a constant, i.e., with $\beta_1 = 0$; and 3) with a linear time trend, i.e., with β_0 and β_1 unknown and estimated from the data. We have marked in bold in the tables, the selected specification for each series, which is based on the t-values of the estimated coefficients in the d-differenced series. In other words, combining the two equalities in Eq. (4) leads to:

$$\widetilde{y}_t = \alpha \widetilde{1}_t + \beta \widetilde{t}_t + u_t, \quad t = 1. 2, \ldots \tag{5}$$

where

$$\widetilde{y}_t = (1 - B)^d y_t; \quad \widetilde{1}_t = (1 - B)^d 1; \quad \widetilde{t}_t = (1 - B)^d t,$$

and u_t in (5) is I(0) by assumption so standard *t*-test apply.

The first observable feature in Table 3 is that the time trend specification is not required in any single case, the intercept being sufficient to describe the deterministic part in all cases. If we look at the values of d, they are very close to 1 in all cases, and the unit root null hypothesis cannot be rejected in the majority of the series. The only two exceptions are "Copper" and "Tin" with d-values equal to 0.97 and 0.94 respectively, and with the confidence bands rejecting the case of $d = 1$ in favour of $d < 1$. Thus, in these two series we observe a very small degree of reversion to the mean. For the remaining cases, since the null of $d = 1$ cannot be rejected, these could be consistent with the weak form of stock market efficiency.

Next, we permit autocorrelation by using Bloomfield (1973). This is a non-parametric technique in the sense that there is no explicit model, simply described in terms of its spectral density function where its logged version approximates very well the log-spectral density of an autoregressive model. This approach has been widely used in the context of fractional integration (see, e.g., Gil-Alana and Robinson, 1997; Gil-Alana and Moreno, 2012; etc.) and the results in terms of the differencing parameter (d) are displayed in Tables 4 and 6

First, we observe that a linear trend is found to be significant for the case of "Gold", with the time trend coefficient being significantly positive. For the remaining cases, the intercept is the only deterministic term. Focusing on the values of d, the values range between 0.97 ("Lead") and 1.01 ("Silver" and "Copper"), and the I(1) hypothesis cannot be rejected in any single case. This is not surprising noting the nonstationary nature of the series and it implies that shocks in the series will have a permanent nature. However, the results reported so far may be biased due to the presence of structural breaks and non linearities. In fact, this is a recurring argument that states that both issues (fractional integration and breaks) are intimately related.[1] Because of that, we use two approaches for determining multiple breaks in the data. In particular, first we use Bai and Perron's (2003) approach, followed then by Gil-Alana's (2008) method, which is basically its extension to the fractional case. In both cases the results are identical, which is not surprising based on the nonstationary I(1) nature of the series under examination.

Table 7 displays the structural breaks for each series. We observe that all the series under investigation are exposed to multiple breaks (at least 3 breaks). While estimating a single global break model in the presence of multiple breaks, the estimate of the break fraction would converge to one of the true break fractions, that is the dominant one. The single structural break point test suggests that these breaks are traced back to the periods, such as 8/04/2011, 14/9/2010, 12/01/2017, 29/07/2010, 6/9/2012, 28/6/2016, 5/08/2010 and 27/3/2015, in the series of gold, silver, aluminium, copper, lead, zinc, tin and nickel respectively.

The break in the gold series could be due to the action of the Federal Reserve's Quantitative Easing 2 (QE-2) which lasted seven months, from November 2010 to June 2011. Around this date, major stock markets including those in the United States, the Middle East, Europe and Asia plunged owing to the fear of the contagion effects of the sovereign debt crisis in Spain and Italy, credit rating worries in France and slow

[1] Articles relating these two issues include, among many others, Diebold and Inoue (2001), Granger and Hyung (2004) Deo et al. (2006), Baillie and Morana (2009), Lahiani and Scaillet (2009), Choi et al. (2010a,b) and Hwang and Shin (2018).

Table 2
Time series under examinations and Descriptive Statistics.

Panel A: Time series under examinations

i) Precious metals			
Series	Starting period	Ending period	N. of observations
Gold	01–11- 2007	20–03- 2020	3232
Silver	01–11- 2007	20–03- 2020	3232
ii) Non-precious metals			
Series	Starting period	Ending period	N. of observations
Aluminium	08–11- 2007	20–03- 2020	3227
Copper	16–11- 2007	20–03- 2020	3221
Lead	11–12- 2007	20–03- 2020	3204
Zinc	01–11- 2007	20–03- 2020	3232
Tin	27–12- 2007	20–03- 2020	3192
Nickel	14–12- 2007	20–03- 2020	3201

Panel [a]B: Descriptive Statistics

	Precious Metal		Non-Precious metal					
	Gold	**Silver**	**Alumin**	**Copper**	**Lead**	**Zinc**	**Tin**	**Nickle**
Mean	10.10	10.53	4.72	5.91	4.76	4.81	7.01	6.75
Median	10.24	10.57	4.70	6.00	4.79	4.75	7.08	6.79
Maximum	10.70	11.20	5.14	6.21	5.15	5.45	7.35	7.20
Minimum	9.21	9.69	4.14	4.91	3.73	3.90	6.13	6.09
Std. Dev.	0.33	0.31	0.17	0.22	0.24	0.34	0.25	0.22
Skewness	−1.03	−0.69	−0.56	−1.87	−1.18	−0.05	−1.17	−0.59
Kurtosis	2.99	2.93	3.94	7.12	5.07	2.53	3.61	2.88
JB Stat.	572.6*	259.0*	285.9*	4143.8*	1309.3*	31.2*	776.9*	190.6*
Obs.	3232	3232	3227	3221	3204	3232	3192	3201

JB denotes the Jarque-Bera test for normality. ***, ** and * denotes significance at 1%, 5% and 10%.
[a] Panel B contains the descriptive statistics of logprices

Table 3
Estimates of d: White noise errors.

i) Precious metals			
Series	No terms	With intercept	With time trend
GOLD	1.00 (0.97, 1.03)	**1.01 (0.98, 1.04)**	1.01 (0.98, 1.04)
SILVER	1.00 (0.97, 1.03)	**0.99 (0.96, 1.01)**	0.99 (0.96, 1.01)
ii) Non-precious metals			
Series	**No terms**	**With intercept**	**With time trend**
ALUMINIUM	1.00 (0.97, 1.02)	**0.98 (0.95, 1.01)**	0.98 (0.95, 1.01)
COPPER	1.00 (0.97, 1.03)	**0.94 (0.92, 0.97)**	0.94 (0.92, 0.97)
LEAD	1.00 (0.98, 1.03)	**0.99 (0.96, 1.02)**	0.99 (0.96, 1.02)
ZINC	1.00 (0.97, 1.03)	**0.98 (0.95, 1.01)**	0.98 (0.95, 1.01)
TIN	1.01 (0.97, 1.03)	**0.97 (0.94, 0.99)**	0.97 (0.94, 0.99)
NICKEL	1.00 (0.97, 1.03)	**0.99 (0.96, 1.02)**	0.99 (0.96, 1.02)

The title "No terms" means that no intercept and no time trend is considered in the model, i.e., $\alpha = \beta = 0$ in Eq. (4); the model with "Intercept" means that only an intercept is required, i.e, $\beta = 0$ in Eq. (4); finally, the model with "a time trend" means that an intercept and a time trend is required so both coefficients α and β in Eq. (4) are estimated from the data. The bold numbers refer to the selected specification among the three cases, and the values in parenthesis are the 95% lower and upper bands for the confidence intervals.

Table 4
Associated coefficients to the models in Table 2: White noise errors.

i) Precious metals			
Series	No terms	With intercept	With time trend
Gold	1.01 (0.98, 1.04)	9.219 (55.98)	–
Silver	0.99 (0.96, 1.01)	9.843 (56.80)	–
ii) Non-precious metals			
Series	**No terms**	**With intercept**	**With time trend**
Aluminium	0.98 (0.95, 1.01)	4.620 (56.20)	–
Copper	0.94 (0.92, 0.97)	5.586 (56.12)	–
Lead	0.99 (0.96, 1.02)	4.556 (55.17)	–
Zinc	0.98 (0.95, 1,01)	4.675 (265.31)	–
Tin	0.97 (0.94, 0.99)	6.457 (56.06)	–
Nickel	0.99 (0.96, 1.02)	6.926 (55.98)	–

The values displayed in this table are those corresponding to the selected specification in Table 2. The values in parenthesis in the third column refer to the t-values of the corresponding estimated coefficients.

economic growth in the US. The cause of the break in the global silver price series is claimed to be that JP Morgan Chase and HSBC caused a massive silver price surge in 2010 when they covered their short positions. That, on January 12, 2017 the US administration filed a historic World Trade Organization (WTO) case against China's illegal subsidies for its domestic aluminium industry could be one of the major causes in structural break in aluminium price series. There was a spike in global 'zinc' occurring around June 28, 2016 owing to supply constraints as the major zinc mines (Century Mine- Australia, Lisheen Mine- Ireland and other Glencore mines) shut down and China shut down zinc and lead mines in parts of Hunan province due to safety and environmental concerns. This might have triggered LME zinc inventories to their 5 year low around the said date. The lead metal price spikes on September 6, 2012 could have been due to supply constraints. Similarly, decreased 'tin' supply to global markets *had also* pushed up benchmark lead *prices.* We also find breaks in copper series upon revival of the global economy after the financial crisis. However, Nickel's weak price performance towards the end of second half of 2015 is due to oversupply from the Philippines and a reduction in Chinese demand owing to the economic slowdown.

We have next evaluated the differencing parameters for each subsample in each of the series. Table 8 refers to the case of white noise errors, while Table 9 displays the results under the assumption of (Bloomfield) weak autocorrelation. We start with the case of white noise errors. We observe a significant time trend in the case of "gold" for the second subsample, and a degree of mean reversion is detected in that subsample. The same evidence of mean reversion is observed for "Silver" during the second subsample. If we look now at the results for the non-precious metals, we see that for these, a single break was detected (i.e., aluminium, copper and tin) and mean reversion is also detected during the second subsamples. This is also observed for "zinc" in the third subsample. However, under the assumption of autocorrelated errors (in

Table 5
Estimates of d: Autocorrelation.

Series	No terms	With intercept	With time trend
i) Precious metals			
GOLD	1.00 (0.96, 1.04)	0.98 (0.94, 1.03)	**0.98 (0.94, 1.03)**
SILVER	1.00 (0.96, 1.04)	**1.01 (0.97, 1.05)**	1.01 (0.97, 1.05)
ii) Non-precious metals			
Series	**No terms**	**With intercept**	**With time trend**
ALUMINIUM	0.99 (0.95, 1.03)	**0.99 (0.95, 1.04)**	0.99 (0.95, 1.04)
COPPER	0.99 (0.95, 1.04)	**1.01 (0.98, 1.05)**	1.01 (0.98, 1.05)
LEAD	0.99 (0.95, 1.04)	**0.97 (0.92, 1.02)**	0.97 (0.92, 1.02)
ZINC	0.99 (0.95, 1.04)	**0.99 (0.95, 1.04)**	0.99 (0.95, 1.04)
TIN	1.00 (0.96, 1.04)	**0.98 (0.93, 1.02)**	0.98 (0.93, 1.02)
NICKEL	0.99 (0.96, 1.04)	**0.99 (0.95, 1.03)**	0.99 (0.95, 1.03)

The title "No terms" means that no intercept and no time trend is considered in the model, i.e., $\alpha = \beta = 0$ in Eq. (4); the model with "Intercept" means that only an intercept is required, i.e, $\beta = 0$ in Eq. (4); finally, the model with "a time trend" means that an intercept and a time trend is required so both coefficients α and β in Eq. (4) are estimated from the data. The bold numbers refer to the selected specification among the three cases, and the values in parenthesis are the 95% lower and upper bands for the confidence intervals.

Table 6
Associated coefficients to the models in Table 3: Autocorrelation.

Series	No terms	With intercept	With time trend
i) Precious metals			
Gold	0.98 (0.94, 1.03)	9.219 (963.21)	0.00046 (3.23)
Silver	1.01 (0.97, 1.05)	9.843 (640.62)	–
ii) Non-precious metals			
Series	No terms	With intercept	With time trend
Aluminium	0.99 (0.95, 1.04)	4.620 (337.40)	–
Copper	1.01 (0.98, 1.05)	5.586 (331.57)	–
Lead	0.97 (0.92, 1.02)	4.557 (233.00)	–
Zinc	0.99 (0.95, 1.04)	4.6756 (265.99)	–
Tin	0.98 (0.93, 1.02)	6.457 (378.01)	–
Nickel	0.99 (0.95, 1.03)	6.926 (337.97)	–

The values displayed in this table are those corresponding to the selected specification in Table 2. The values in parenthesis in the third column refer to the t-values of the corresponding estimated coefficients.

Table 9) the confidence intervals are so wide that we cannot confirm this evidence in any single case. This evidence of mean reversion when breaks are taken into account is consistent with the lack of power of the unit root tests under this type of alternatives (Perron and Phillips, 1987; West, 1987; Perron, 1989; etc.) and also with the literature that relates fractional integration and breaks (Sibbertsen, 2004; Granger and Hyung, 2004; Choi et al., 2010a,b; Mayoral, 2012; etc.).

6. Conclusions

The price dynamics of precious and non-precious metals have long been a matter of popular concern following the emergence of metals as an investment asset class in recent years (Beckmann et al., 2019; Baumöhl and Lyócsa, 2017). This study investigates long memory features of precious and non-precious metal price series from November 01, 2007 to March 20, 2020 controlling for structural breaks and non-linearities in the price series. We apply techniques based on fractional integration after accommodating underlying autoregressive behaviour to investigate the long term dynamics of the series. From the results, we fail to reject the unit root null hypothesis in most of the cases, given that the values of d are close to 1 for most of the metals with the exception of Copper and Tin. Thus, Copper and Tin exhibit a small degree of reversion to the mean, with orders of integration slightly, albeit significantly below 1. We permit autocorrelation using the method of Bloomfield (1973) and further we observe that a linear trend is found to be significant for the case of Gold, though the unit root null hypothesis

Table 7
Structural breaks.

Series	Global 3 breaks vs. None		Global 1 Break vs. None	
	No. of breaks	Break dates	No. of breaks	Break dates and probable cause
i) Precious metals				
GOLD	3*	09/09/2009 08/04/2011 17/04/2018	1*	8/04/2011 [a] Quantitative Easing 2- QE 2
SILVER	3*	14/09/2010 15/04/2013 20/02/2015	1*	14/9/2010 [b] Financial Fraud detection
ii) Non-precious metals				
ALUMINIUM	3*	23/09/201 19/06/2014 12/01/2017	1*	12/01/2017 [c] WTO case against China
COPPER	3*	29/07/2010 08/07/2015 18/07/2017	1*	29/07/2010 [d] Global economic recovery
LEAD	3*	13/10/2009 06/09/2012 29/09/2016	1*	6/9/2012 [e] Chinese import demand and sustained
ZINC	3*	10/09/2009 09/08/2013 28/06/2016	1*	28/6/2016 [f] supply constraints and emerging market demand surge
TIN	3*	05/08/2010 17/10/2014 17/08/2016	1*	5/08/2010 [d] Global economic recovery
NICKEL	3*	15/02/2010 27/03/2015 02/01/2018	1*	27/3/2015 [g] oversupply and reduction in Chinese demand

[[a] Federal Reserve's second round of Quantitative Easing 2 (QE-2).
[b] JP Morgan Chase and HSBC covered their massive short positions, which caused a massive silver price surge in 2010.
[c] The Obama administration filed a historic WTO case against China's illegal subsidies for its domestic aluminium industry.
[d] Recovery of global copper and tin metal price after the 2008 global financial crisis.
[e] Sustained increase in Chinese imports as car sales were rising and general positive sentiments in the market.
[f] Surge in zinc prices in second half of 2016 was due to Falling production, declining LME zinc stocks and emerging market demand surge are the major causes.
[g] Nickel's weak price performance towards the end of second half of 2015 is due to oversupply by the Philippines and reduction in Chinese demand owing to economic slowdown.
Note: We allow for a maximum of 3 breaks and 1 global in each series. Break test options: Trimming 0.15, Max. breaks 3 and 1, Sig. level 0.01. Allow heterogeneous error distributions across breaks. * indicates the number of break points are found to be statistically significant at sig. level 0.01.

Table 8
Estimates of d for each subsample and each series: White noise errors.

i) Precious metals				
Series		No terms	With intercept	With time trend
GOLD	1s	0.99 (0.93, 1.06)	**0.98 (0.92, 1.06)**	0.98 (0.92, 1.06)
	2s	0.99 (0.93, 1.06)	0.92 (0.87, 0.99)	**0.92 (0.86, 0.99)** *
	3s	1.00 (0.95, 1.05)	**1.01 (0.96, 1.07)**	1.01 (0.96, 1.07)
	4s	0.99 (0.93, 1.06)	**1.02 (0.97, 1.08)**	1.02 (0.97, 1.08)
	5s	0.99 (0.94, 1.06)	**1.02 (0.86, 1.08)**	1.02 (0.86, 1.08)
	6s	0.99 (0.93, 1.06)	**1.04 (0.98, 1.12)**	1.04 (0.98, 1.12)
SILVER	1s	1.00 (0.95, 1.05)	**0.98 (0.93, 1.03)**	0.98 (0.93, 1.03)
	2s	0.99 (0.94, 1.04)	**0.91 (0.87, 0.97)** *	0.92 (0.87, 0.97)
	3s	1.00 (0.96, 1.03)	**1.04 (1.00, 1.08)**	1.04 (1.00, 1.08)
ii) Non-precious metals				
Series		No terms	With intercept	With time trend
ALUMINIUM	1s	1.00 (0.97, 1.03)	**0.99 (0.96, 1.02)**	0.99 (0.96, 1.02)
	2s	1.00 (0.95, 1.05)	**0.94 (0.89, 0.99)** *	0.94 (0.89, 0.99)
COPPER	1s	1.00 (0.95, 1.05)	**0.96 (0.92, 1.01)**	0.96 (0.92, 1.01)
	2s	1.00 (0.97, 1.04)	**0.91 (0.88, 0.94)** *	0.91 (0.87, 0.94)
LEAD	1s	1.00 (0.95, 1.06)	**1.01 (0.95, 1.06)**	1.01 (0.95, 1.06)
	2s	1.00 (0.97, 1.04)	**0.97 (0.93, 1.01)**	0.97 (0.93, 1.01)
	3s	1.00 (0.96, 1.05)	**0.96 (0.92, 1.01)**	0.96 (0.91, 1.01)
ZINC	1s	0.99 (0.93, 1.06)	**0.97 (0.91, 1.04)**	0.97 (0.93, 1.04)
	2s	1.00 (0.96, 1.05)	**0.98 (0.93, 1.03)**	0.95 (0.90, 1.03)
	3s	1.00 (0.95, 1.05)	**0.94 (0.90, 0.99)** *	1.00 (0.96, 0.99)
	4s	1.00 (0.95, 1.05)	**1.00 (0.96, 1.06)**	1.00 (0.96, 1.06)
TIN	1s	1.00 (0.95, 1.06)	**0.97 (0.92, 1.03)**	0.97 (0.92, 1.03)
	2s	1.00 (0.97, 1.03)	**0.96 (0.93, 0.99)** *	0.96 (0.93, 0.99)
NICKEL	1s	1.00 (0.94, 1.06)	**0.99 (0.93, 1.06)**	0.99 (0.93, 1.06)
	2s	1.00 (0.96, 1.04)	**0.98 (0.94, 1.03)**	0.98 (0.94, 1.03)
	3s	0.99 (0.94, 1.06)	**0.95 (0.90, 1.01)**	0.95 (0.90, 1.01)
	4s	0.99 (0.94, 1.06)	**1.01 (0.96, 1.07)**	1.01 (0.96, 1.07)

In bold the selected specification and with *: evidence of mean reversion at the 5% level.

cannot be rejected in any single case. Thus, using the whole sample size, the results support the hypothesis of nonstationarity and permanency of the effects of shocks in the series. We account for structural breaks and non-linearities in the price series using Bai and Perron's (2003) and Gil-Alana's (2008) methods with identical results from both approaches, which is not surprising based on the nonstationary I(1) nature of the series under examination. We observe that all the series under investigation are exposed to multiple breaks (at least 3 breaks), under both the assumptions of white noise errors and (Bloomfield) autocorrelation. Results for the case of white noise errors shows a time trend in the case of "Gold" for the second subsample, and a small degree of mean reversion is detected for "Silver" "Aluminium", "Copper", "Tin" and "Zinc" during

Table 9
Estimates of d for each subsample and each series: Autocorrelated errors.

i) Precious metals				
Series		No terms	With intercept	With time trend
GOLD	1s	0.98 (0.89, 1.10)	0.92 (0.81, 1.05)	**0.92 (0.80, 1.05)**
	2s	0.98 (0.89, 1.11)	0.91 (0.82, 1.02)	**0.91 (0.81, 1.02)**
	3s	0.99 (0.92, 1.09)	**0.97 (0.89, 1.08)**	0.97 (0.89, 1.08)
	4s	0.97 (0.88, 1.10)	**1.04 (0.95, 1.14)**	1.04 (0.95, 1.13)
	5s	0.98 (0.90, 1.10)	**0.97 (0.89, 1.09)**	0.97 (0.89, 1.09)
	6s	0.99 (0.88, 1.09)	1.00 (0.91, 1.11)	**1.00 (0.90, 1.11)**
SILVER	1s	0.99 (0.92, 1.09)	**0.99 (0.92, 1.09)**	0.99 (0.92, 1.09)
	2s	0.98 (0.91, 1.09)	**1.00 (0.91, 1.10)**	1.00 (0.91, 1.10)
	3s	0.99 (0.94, 1.05)	**0.98 (0.93, 1.05)**	0.98 (0.93, 1.05)
ii) Non-precious metals				
Series		No terms	With intercept	With time trend
ALUMINIUM	1s	0.99 (0.95, 1.04)	**1.00 (0.95, 1.05)**	1.00 (0.95, 1.05)
	2s	0.99 (0.92, 1.08)	**0.94 (0.87, 1.05)**	0.94 (0.87, 1.05)
COPPER	1s	0.99 (0.90, 1.07)	**1.03 (0.97, 1.10)**	1.03 (0.97, 1.10)
	2s	0.99 (0.95, 1.04)	**0.97 (0.92, 1.02)**	0.97 (0.92, 1.02)
LEAD	1s	0.99 (0.92, 1.08)	**0.98 (0.90, 1.06)**	0.98 (0.90, 1.06)
	2s	1.01 (0.94, 1.06)	**0.98 (0.91, 1.07)**	0.98 (0.91, 1.07)
	3s	0.99 (0.93, 1.06)	**0.95 (0.88, 1.03)**	0.95 (0.88, 1.03)
ZINC	1s	0.97 (0.88, 1.07)	**0.97 (0.87, 1.08)**	0.97 (0.87, 1.08)
	2s	0.99 (0.92, 1.07)	**1.00 (0.91, 1.09)**	1.00 (0.91, 1.09)
	3s	0.99 (0.92, 1.09)	**1.00 (0.83, 1.09)**	1.00 (0.83, 1.09)
	4s	0.99 (0.92, 1.08)	**1.03 (0.96, 1.11)**	1.03 (0.96, 1.11)
TIN	1s	0.99 (0.92, 1.08)	**0.95 (0.88, 1.04)**	0.95 (0.88, 1.04)
	2s	1.00 (0.96, 1.05)	**0.98 (0.94, 1.04)**	0.98 (0.94, 1.04)
NICKEL	1s	0.99 (0.90, 1.10)	**0.97 (0.89, 1.06)**	0.97 (0.89, 1.06)
	2s	1.00 (0.94, 1.05)	**0.94 (0.88, 1.02)**	0.94 (0.88, 1.02)
	3s	0.98 (0.91, 1.08)	**0.94 (0.87, 1.04)**	0.94 (0.87, 1.04)
	4s	0.99 (0.90, 1.08)	**1.06 (0.97, 1.11)**	1.06 (0.97, 1.11)

In bold the selected specification and with *: evidence of mean reversion at the 5% level.

some of the subsamples. However, under the assumption of autocorrelated errors the confidence intervals are so wide that we cannot confirm this evidence in any single case. Nevertheless, the possibility of mean reversion under potential breaks in the metal returns is a line of research that should deserve further attention in future research.

Declaration of competing interest

I write on behalf of the authors to submit that we have no conflicts of interest to disclose.

Data availability

Data will be made available on request.

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