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The asymmetric effects of real interest rates and US dollar on gold prices

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RESUMO

Historicamente, o ouro desempenhou um papel central em vários planos. Serviu de reserva de valor, meio de pagamento, serviu de base ao sistema de *Bretton Woods*, entre outros.

Uma vez que o ouro é comumente aceite como um ativo de refúgio, nesta dissertação são analisados os determinantes do preço do ouro, com especial enfoque nas taxas de juro reais.

Para modelizar o preço do ouro, foi estimado um modelo considerando como variáveis explicativas: taxas de juro reais da economia norte-americana e alemã, taxa de inflação de ambos os países, o índice S&P500, o índice do dólar americano e os índices de incerteza EPU, VIX e GPR. Dentro deste conjunto de variáveis foi avaliado o possível efeito assimétrico das taxas de juro reais de ambas economias e do índice cambial do dólar sobre o preço do ouro.

No longo prazo, variações negativas da taxa de juro real alemã demonstram-se estatisticamente significativas para explicar o preço do ouro. No curto prazo, variações tanto positivas como negativas da taxa de juro real norte-americana exercem um impacto negativo sobre o preço do ouro.

Relativamente ao índice cambial do dólar, tanto no curto como no longo prazo, há evidência estatística deste influenciar o preço do ouro. No longo prazo, variações negativas no valor do dólar influenciam negativamente o preço do ouro. No curto prazo, variações positivas do dólar levam a uma diminuição do preço do ouro. Variações negativas do dólar, no curto prazo, não demonstram uma relação clara sobre o ouro.

Palavras-chave: Preço do ouro, taxa de juro real, índice do dólar, NARDL, ativo de refúgio, inflação.

ABSTRACT

Historically, gold has played a central role at several levels. It has served as a store of wealth, as a mean of payment, and was the base in the Bretton Woods system, among others.

Once gold is commonly accepted as a safe haven asset, in this paper the gold price determinants are analyzed, with special focus on the real interest rates.

In order to model gold prices, an econometric model was estimated, considering the following variables: real interest rates from Germany and the United States, inflation from both economies, the S&P500 index, the dollar index and the uncertainty measures EPU, VIX and GPR. Within this set of variables, it was assessed the possible existence of asymmetric effects of the real interest rates from both economies and the dollar index on gold prices.

In the long-term, negative changes in the German real interest rate have proven to be statistically significant to explain gold prices. In the short-term, both positive and negative changes of the US real interest rate exert a negative impact on gold prices.

In respect to the dollar index, both in the short- and long-term, there is statistical evidence that this variable influences the gold prices. In the long-term, negative changes in the value of the dollar exert a negative impact on gold prices. In the short-term, positive changes of the dollar contribute to a decrease in gold prices. The impact of negative changes in the US dollar value, in the short-term, to gold is not evident.

Keywords: Gold prices, real interest rates, US dollar index, NARDL, safe haven, inflation.

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1. INTRODUCTION

Gold has historically played a significant role contributing to the development of the modern economy as we know it today. Gold has, throughout the years, served as a store of value, as a mean of payment, as a symbol of wealth, as a safe haven in times of market and economic distress, among others. Additionally, gold has also been used as a monetary and financial instrument. During the gold standard era (1870-1914), each central bank fixed the value of its currency relative to the quantity of its reserves in gold. To keep their gold reserves increasing and money supply growing, central banks had to trade domestic assets in exchange for gold. As a result, in this period, the gold standard mechanism also functioned as a control for inflation since central banks could only increase money supply accordingly to their gold reserves. Due to gold's limited and scarce nature, money supply growth had to be gradual (Krugman *et al.*, 2012).

Later on, in the Bretton Woods system (1944-1973), the value of the US dollar was fixed against gold ($35 per ounce), and other currencies had their value fixed against the American dollar (Krugman *et al.*, 2012). While gold lost some importance after the collapse of the Bretton Woods system, it still maintains vital functions in our modern economy. It continues to be traded in financial markets, and there is still some consensus shared by investors that gold can serve as a hedge against inflation or in situations of high volatility. Furthermore, most central banks worldwide have been increasing their gold reserves in recent decades, which clearly reflects the continued importance of gold (see Figure A1 in the Appendix). According to a recent survey conducted by the World Gold Council, 25% of central banks plan to continue increasing their gold reserves in the upcoming years (World Gold Council, 2022). The main reason central banks attribute to the unmoving importance of gold is its historical position, followed by its performance as a safe haven in times of market stress (World Gold Council, 2022). According to the Financial times, during the year of 2022 central banks increased their gold reserves at the "*fastest pace since 1967*" (Dempsey, 2022). Analysts attribute this increase primarily to Russia and China's efforts to diversify away from the US dollar, following the geopolitical turmoil that arrived in Europe since Russia invaded Ukraine. In Russia's case, not only has the Russian central bank increased their gold reserves, but private individuals have also increased their demand for gold coins and bars, reflecting the climate of mistrust (Stognei & Hook, 2023).

For all the reasons mentioned above, gold has been a topic of interest for financial market participants and policy makers for years, namely trying to understand precisely which determinants influence gold prices and whether gold can act as a hedge of a safe heaven or not. This question becomes even more relevant, if we consider that gold has failed to fulfill its role as a hedge against inflation and against economic, political, and financial instability, in the current year of writing (2022), as it was expected (see Figures A2, A3 and A4 in Appendix). The geopolitical uncertainty is currently very high, with the increasing prospects of a long-armed conflict between Russia and Ukraine, plus the rampant tensions between China and Taiwan. Besides all the political turmoil, inflation has never been this high since the euro has entered in circulation, and the prospects of an economic recession are becoming more realistic each day. Nevertheless, gold returns are quite negative. The year-to-date gold returns measured in the LBMA (London Bullion Market) register a negative value of -7.36% and -8.40% when measured in the US market (World Gold Council, 2022).

Based on extensive existing literature regarding the determinants of gold prices, there is only a few papers that consider real interest rates as an actual determinant. One of them is Apergis *et al.* (2019).

This study aims to contribute to the existing literature by adding some important insights regarding the relationship between real interest rates and gold prices, more precisely, this study will focus on the possible existence of asymmetric effects on gold prices. As gold is commonly traded as a financial instrument, and because financial markets normally react more aggressively to negative impacts than to positive ones, it is reasonable to consider that some important economic variables, such as the value of real interest rates, might have asymmetric impacts on the noble metal prices.

Moreover, this paper will consider real interest rates from Germany, once this economy can be considered to be safer than the United States of America itself, as demonstrated below in Table 1. Rating agencies such as S&P and Fitch, both attribute rating AA+ to the US economy, as for Germany the rating remains AAA. The Fitch agency has recently downgraded the US rating from AAA to AA+ due to some "*fiscal deterioration*" through a high and increasing level of government debt (Clarfelt, 2023)

Table 1: USA and German long term credit ratings by Moody's, S&P and Fitch

Long Term Ratings						
	Moody's		S&P		Fitch	
	Rating	Date	Rating	Date	Rating	Date
Germany	Aaa	05/07/2000	AAA	13/01/2012	AAA	10/08/1994
USA	Aaa	02/08/2011	AA+	05/08/2011	AA+	01/08/2023

Several other papers have analysed the impact that different determinants have on gold prices. Among the literature regarding this subject, the papers that relate the most to the following dissertation are two, namely the one conducted by Apergis *et al.* (2019). This paper focus on the impact that the real interest rates, from the G7 economies, might have on gold prices. A conclusion obtained in this dissertation matches a conclusion achieved by Apergis *et al.* (2019), more precisely that there is negative and significant relationship between the lagged value of US real interest rates and gold prices.

Other study that is closely associated to this dissertation is the paper carried out by Bilgin *et al.* (2018), in the sense that these authors investigate the possible existence of asymmetric effects between uncertainty measures and gold prices using an NARDL model. This thesis also estimates an NARDL to scrutinize if there is any asymmetric impact of real interest rates or the American US dollar on gold prices.

The main conclusions reached in this thesis correspond to negative changes in the German real interest rate being statistically significant to explain gold prices, in the long-term.

In the short-term, both positive and negative changes of the US real interest rate exert a negative impact on gold prices.

These two results sustain the hypothesis that indeed real interest rates from the two safest economies might influence the shiny metal prices.

With respect to the American US dollar index, both in the short- and long-term, there is statistical evidence that this variable influences gold prices. In the long-term, negative changes in the value of the dollar exert a negative impact on gold prices. In the short-term, on the other hand, positive changes of the dollar contribute to a decrease in gold prices. This conclusion goes along with the findings obtained by other researchers and that are summarized in the literature review.

Finally, this paper is organized as it follows: first, in section II, it is presented a compound of literature regarding the topic presented in this paper to facilitate the understanding of this paper and build upon the existent knowledge. Section III gives a description of the data employed and all the tests conducted to guarantee the econometric model could be correctly estimated.

In section IV, the estimation of the econometric model itself is presented as also all the diagnostic tests necessary to consider the model valid. To conclude, in sections V and VI, this thesis ends with the presentation and interpretation of the main results achieved.

2. LITERATURE REVIEW

It is commonly accepted that gold can act as a hedge or as a safe haven against inflation or in times of high uncertainty. It is relevant, before all, to clearly understand the difference between the hedge and safe haven properties of gold. Baur and Lucey (2010) defined and tested statistically these financial properties of gold for the US, UK and Germany equity and bond markets in the time spanning 1995 to 2005. Following the author's definitions, the hedge property is defined as *"as an asset that is uncorrelated or negatively correlated with another asset or portfolio on average*". In the other hand, a safe haven is defined as "*an asset that is uncorrelated or negatively correlated with another asset or portfolio in times of market stress or turmoil".* At first glance, one might think that gold is very most likely to perform as a safe haven, then as a hedge. This thought seems to be logic since in a scenario where solid economic growth and low levels of uncertainty co-exist, investors will tend to maximize their returns, instead of worrying about potential losses in the future, when the economic outlook does not look so appellative. Gomis-Porqueras *et al.* (2022) confirms this first idea. In agreement with the authors, gold tends to act as a weak hedge for stock markets, Euro government bond spreads and oil prices during periods of normality. Nevertheless, there is evidence that gold effectively performs its job as a hedge and as a safe haven in periods of recession. Baur and McDermott (2010) similarly reach the conclusion that investors demand for the shining asset tends to increase after short lived and extreme negative shocks. The safe haven property of gold is easier to identify when using daily data, in contrast to weekly or monthly data, where the safe haven property is not so straightforward to perceive (Baur and McDermott, 2009). Based on the two after mentioned reports, it appears that gold is more commonly viewed as a safe haven rather than a hedge.

Building upon the definitions from Baur and Lucey (2010), there is an extensive amount of literature testing for the hedge or safe haven properties of gold in different markets, against others financial instruments or against currencies.

Capie *et al.* (2005) analyzed to which extent the yellow metal could act as a hedge for the US dollar. The pertinence of this question is twofold. First, one reason why a US dollar depreciation can potentially lead to an increase in gold prices is that gold is primarily quoted in US dollar, which means that the relative price of gold becomes lower for foreign investors when the US dollar loses values. Second, gold is globally accepted as a safe and very liquid asset and can, consequently, be used as a way to protect investors again the exchange rate risk. Capie *et al.* (2005) arrives at the conclusion that gold has acted as a hedge against the US dollar, however, the hedge property of gold against the dollar has been changing over the years. Bukowski (2016), Elfakhani *et al.* (2009), Qian *et al.* (2019), Chiang (2022), Zhu *et al.* (2018) and Gomis-Porqueras *et al.* (2022) all find statistical evidence of an interdependence between the US dollar exchange rate and gold prices, more precisely a negative causality between them. The available evidence suggests that when the value of the US dollar decreases, the price of gold generally increases, likely due to the two reasons mentioned before.

Apart from the US dollar, other currencies have been considered as safe haven assets in comparison to gold, such as the Swiss franc. Baur and McDermott (2016) examined both the US dollar and the Swiss franc in their study and concluded that the Swiss franc was the only safe haven asset that displayed positive returns among all crisis periods (Baur and McDermott, 2016). As stated by the authors, the CHF is a strong safe haven for the MSCI world stock index and a weak safe haven for the S&P 500, which means, the Swiss currency tends to be used by global investors as a safe haven, while the US dollar, in the other hand, is primarily used for the US market (Baur and McDermott, 2016).

Other than the relation between the US dollar and gold prices, there exists a vast body of literature concerning the hedge or safe haven properties of gold against other assets, such as stock indices or bond indices. In times of market distress investors will attempt at the best of their capability to minimize the potential losses of their portfolios. It matters, in this order, to analyze if gold can effectively act as a safe haven in this situation, besides protecting against depreciations of the US dollar. In this regard, Themba *et al.* (2020) took a very deep look into the correlation movements between a large set of global stock indices and the price of gold. The conclusions reached are somewhat ambiguous. Contrary to what some might believe, a sudden drop in the stock market does not necessarily lead to an increase in the gold price, as noted by Themba *et al.* (2020). Themba *et al.* (2020) concludes that stock markets seem to maintain a positive correlation to gold prices. On the other side of the coin, bond market results show that bonds and gold prices tend to move contrarily. These results are contradictory to those obtained from Bukowski (2016), Baur and Lucey (2010) and Qian *et al.* (2019). Bukowski (2016) and Qian *et al.* (2019) concluded that there is a negative causality between the S&P 500 index and gold prices, as Baur and Lucey (2010) stated that gold acts as a safe haven for stocks, even if for a very short period of time (15 trading days) but does not function as a safe haven for bonds.

According to Beckmann *et al.* (2019), the role of gold underwent a significant transformation following the global financial crisis of 2007/2008, especially in the aftermath of the Lehman Brothers collapse in 2008. The authors confirm that gold performed as an instrument that could protect investors before the financial crisis, but after the financial crisis, gold tends to co-move with other financial instruments, particularly with stocks and bonds, meaning that gold has lost its ability to hedge against negative movements in financial markets.

Relative to the safe haven property of gold against stocks or bonds there appears to be some contradictory ideas and conclusions. Therefore, it is unclear whether gold can effectively protect investors against negative movements in financial markets.

Besides determining whether gold can indeed function as a safe haven, it is also relevant to understand if these financial properties of gold hold true across various regions of the globe. Baur and McDermott (2010) scrutinize if the financial properties of gold, namely its hedge or safe haven characteristics, differ among developed and emerging economies. The authors found that gold appears to be a safe haven for most developed economies but not for emerging economies. In times of market turbulence, investors will tend to reallocate their investments from countries with weaker credit quality and a higher risk of default to economies more capable of withstanding financial and economic recessions. This movement is commonly called *flight-to-safety*. It is therefore expectable that gold does not play a significant role as a safe haven in these economies, as stated by Baur and McDermott (2010).

Gold tends to be considered a good financial safe haven instrument. According to Baur and Lucey (2010), while there is no theoretical evidence supporting this financial capacity of gold, one major explanation could be that gold was "*among the first forms of money and was traditionally used as an inflation hedge*" (Baur and Lucey, 2010). In order to access this form of using gold as a protection against inflation, Murach (2019) studied the impact of an excess of global liquidity, measured as the difference between real output and money supply, in gold prices.

In fact, an expansive monetary policy along with low real activity growth, can in the medium/long term conduct to inflationary pressures. This statement is also supported by the quantity theory of money[1], which explicitly states that if money supply surpasses the growth of economic activity, the only possible adjustment is through the price level, meaning a rise in the consumer price index (Friedman, 1956). Inflationary pressures can be created from diverse sources, being one of them an excess of global liquidity. Murach (2019) concludes that, in fact, excess global liquidity demonstrates a positive long-term relationship with real gold prices.

[1] (M)*(V) = (P)*(T), where M = Money supply, V = Velocity of money circulation, P = Average price level and T = Volume of transactions (Friedman, 1956).

Apart from excess liquidity there are some other inflationary sources, such as oil prices pressures. An increase in oil prices, if persistent, will automatically lead to an increase in firm's production costs that, ultimately, will have repercussions on the price level. In this sense, some authors investigated the correlation between gold and oil prices. Bukowski (2016), Apergis *et al.* (2019) identified a positive causality between oil prices and gold prices, which represents another evidence that gold acts as a hedge against inflationary movements. Białkowski *et al.* (2015) explains that the boom in gold prices (1979-1982) was most likely caused by the second oil crisis as it generated *"skyrocketing inflation"*. There seems to be some accordance regarding the hedge property of gold against high levels of inflation. Nevertheless, looking at Figure A4 in the Appendix, we can conclude that even though inflation kept increasing in the year of 2022, the price of gold showed a downfall tendency, after reaching its peak of 2039,1$/oz shortly after the Russian military invasion in Ukraine (24th of February 2022). The fact that gold spot prices reached its highest price immediately after the Russian aggression reflects another safe haven capability of gold, namely against financial, economic, and political turmoil. Several other authors have studied gold's relation to uncertainty. The relation between gold prices and macroeconomic uncertainty will be addressed forward in this report.

Returning to the relation among gold prices and inflation, Zhu *et al.* (2018) found out that gold worked as a hedge against inflation pressures for the United Kingdom only for the period comprehended between 1985-1997. After 1997, gold prices demonstrated an insignificant relationship with respect to inflation. The same conclusion was obtained for the US economy, where gold prices did not hedge against inflation for the period between 2003-2015, period when inflation and inflation expectations where relatively low and stable according to Zhu *et al.* (2018). Elfakhani *et al.* (2009) also stated that inflation maintained a positive relation to gold prices in the 1980's but it turned negative in the 1990's, meaning that gold was unable to keep investors purchasing power after the 90's. Valadkhani *et al.* (2022) additionally stated that gold returns sensitivity to inflation has diminished specially in the period comprehend between 1981-2021, period where inflation was relatively low and stable. Nonetheless, Valadkhani *et al.* (2022) concluded that there is evidence of a positive long-term relation between gold returns and inflation in the period between 1969-2021.

Batten *et al.* (2013) acknowledged a similar and more striking conclusion, namely that while gold was highly sensitive to inflation in the 1980's, this sensitivity has gradually disappeared. The authors refer that if the decade of 1980 was excluded from the data set, there would be no causality between inflation and gold prices. These conclusions corroborate what was seen during the 2022-year period, with the gold prices showing no sensitivity to the high levels of inflation. Batten *et al.* (2013) also concluded a very interesting point regarding gold's sensitivity to consumer price index, more precisely that gold's reaction to inflation seems to be influenced by interest rate changes. This point is of extreme relevance, in the sense that this paper will focus more on the investor's choice between gold as a safe haven or the most important risk-free assets, namely investing in the US and German economies.

Real interest rates[2] can influence investors decisions when it comes to the purchase of gold or any other financial instrument. As seen before, gold has historically acted as a safe haven against inflation, even though its sensitivity to higher prices has, more or less, disappeared in recent years (Batten *et al.*, 2013). Even with high levels of inflation investors can be faced with a dilemma. If real interest rates are positive, meaning that investors returns deducted from inflation will still be positive, would, in this scenario, investors still be interested in buying gold in detriment of risk-free assets, such as US or German government bonds that secured them a certain fixed return if held to maturity?

According to Baur and McDermott (2016) bonds could be more appealing for investors for several reasons, such as the fact that if investors hold bonds until maturity, they will receive a fixed and certain return, as gold, on the other hand, does not offer a fixed and certain return. Instead, gold prices show some volatility. Besides the price volatility, we must also take into consideration the storage cost of gold and the bid-ask spread that can be wider for gold in the spot markets, when compared to the US treasuries (Baur and McDermott, 2016).

Baur and McDermott (2016) consider that gold can protect against another types of risks that bonds cannot, such as *"inflation, currency risk and, perhaps most importantly, default risk"*. Given this, one might expect that if real interest rates are positive, even though inflation levels might be high as well, investors would prefer to purchase risk-free assets and not gold.

Apergis *et al.* (2019) analyzes the real interest rate as one driver of gold prices. As referenced by Apergis *et al.* (2019), there are some theoretical studies that approach this thematic, such as Fortune (1987, as cited in Apergis *et. al*, 2019). As reported by this study, an expected increase in the real interest rate in the future will guide to lower gold prices. This tend to happen because, as real interest rates are expected to increase, investors will tend to sell gold in their portfolio to buy assets with higher expected yields.

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[2] Real interest rates correspond to the nominal interest rate deducted from inflation. Calculating real interest rates can be simplified by using the Fischer equation: $(1 + \mathrm{i}) = (1 + \mathrm{r}) \times (1 + \pi)$, where i = nominal interest rate, r = real interest rate and π = inflation.

On the other hand, Apergis *et al.* (2019) also refers to empirical studies about the same topic that point to different conclusions. One example is Lawrence (2003, as cited in Apergis *et. al*, 2019). The author infers that there is no statistically significant relationship between some financial variables, such as real interest rates and gold returns.

To extend the knowledge on the relationship between gold prices and real interest rates, Apergis *et al.* (2019) tests if there is any significant relationship between real interest rates and gold prices for the period covering 1975-2016 for the G7[3] economies. The main conclusions reached by this author point to a positive causality among real interest rates and gold prices for all countries considered. Nevertheless, the econometric model applied also suggests "*a negative significant relationship between the change in the lagged value of real interest rates and the change in the lagged value of gold prices in both regimes, with the impact being stronger in the recessionary phase*", meaning that gold can act as a hedge in recessionary times, when central banks are forced to decrease nominal interest rates.

Valadkhani *et al.* (2022) found evidence of the 10-year US treasury interest rate being inversely related to gold prices, meaning that if the 10-year US treasury interest rate falls, gold prices would most likely increase. This negative causality between the 10-year US treasury yield and gold prices can be seen in Figure A5 in the Appendix, more precisely from year 2007 onwards.

According to Valadkhani *et al.* (2022), gold tends to perform well under two conditions: high levels of inflation, defined as monthly inflation exceeding 0,55%, and relatively low interest rates.

This leads to the idea that gold will potentially perform well as a safe haven depending on the recession type.

The economy can experience different types of recessions, including supply-side recessions and demand-side recessions, each with unique characteristics and effects on the economy. According to Sorensen and Whitta-Jacobsen (2010) if there is a temporary negative supply shock caused, for example, due to a rise in production costs or a disruption in supply chains, this will lead to stagflation[4] in the short-term. Inflation will increase because supply is now lower when compared to demand and output will decrease because central banks will keep increasing interest rates to control inflation and fulfill their mandate.

[3] US, UK, Germany, Canada, Japan, France, Italy.
[4] A period combining rising inflation and falling output (Sorensen and Whitta-Jacobsen, 2010).

Conversely, if the economy is face with a negative and temporary demand shock, because, for example, agents become more pessimistic regarding the future, this will reduce output and the price level, meaning output and inflation will be below their long-run equilibrium (Sorensen and Whitta-Jacobsen, 2010). Once the aggregate demand recovers, the economy will potentially experience a boom because actual inflation and expected inflation are below their target, which allows central banks to reduce or keep real interest rates relatively low until inflation and expected inflation reached their target (Sorensen and Whitta-Jacobsen, 2010).

As per Valadkhani *et al.* (2022), gold will potentially perform better when inflation is high and interest rates are lower. Nowadays, it is difficult for high inflation and lower interest rates to coexist simultaneously once central banks have very clear mandates to keep inflation at its target. Despite this, there are cases where central banks may delay the decision to raise interest rates even with increasing inflation.

According to Apergis *et al.* (2019), gold functions better as a safe haven against real interest rates during recessions. In times of normality, defined by the authors as "*a booming economy*", there is evidence of a positive relation between real interest rates and gold prices among all G7 economies (Apergis *et al.*, 2019). As stated above, the authors also found evidence of a positive association between inflation and inflationary pressures caused by oil prices to gold prices. The question remains as to what gold is more responsive to during recessionary times, specifically whether it is inflation or to real interest rates.

Figure A6 in the Appendix depicts the relationship between the main recessions[5] that affected the US economy and the monthly average of gold prices along the sample period used (01/1990 – 03/2023). Indeed, after the interest rates reduction as a consequence of the global financial crisis (2007 – 2008), gold prices went up as we can see in Figure A7 in the Appendix. This supports Apergis *et al.* (2019) conclusion that gold can act as a safe haven against real interest rates in times of recession.

As seen before, gold prices also appear to be influenced by the degree of uncertainty. Regarding this topic, several authors have already studied the impact that financial, political, geopolitical, and macroeconomic uncertainty have on the noble metal prices. Baur and Smales (2020) studied how various financial assets prices reacted to changes on the geopolitical risk index (GPR) of Caldara and Iacoviello (Caldara and Iacoviello, 2022). The GPR index

[5] The US recession index is a binomial index that indicates if the US economy was or not in recession in a particular month. An index value of 1 signifies a recession, while an index value of zero represents a month of expansion, according to the measures of the National Bureau of Economic Research (NBER). This index was retrieved from Bloomberg (USRINDEX).

considers geopolitical risk as the risk "*of wars, terrorist attacks and tension between states*". Baur and Smales (2020) concluded that contrarily to what happens to other assets when the GPR index rises, precious metals, such as gold and silver, are positively related to the index, meaning that gold can actually hedge against an increase in geopolitical agitation.

In their study, Bilgin *et al.* (2018) investigated the relationship between measures of uncertainty and the behavior of gold. The authors considered a vast number of uncertainty measures, such as volatility index (VIX), skewness (SKEW), global economic policy uncertainty (EPU) and the partisan conflict index (PC) and evaluate the impact that changes in these uncertainty measures have on gold prices. The authors found evidence of a positive relation between the EPU index and gold prices, meaning that an increase in the economic and political uncertainty level is plausible to lead to an increase in gold prices. Among all uncertainty measures considered, Bilgin *et al.* (2018) arrives at a verdict that *"only positive changes in the global EPU index exert a significant positive impact on gold prices".*

Additionally on this subject, Beckmann *et al.* (2019) stated that macroeconomic uncertainty and uncertainty regarding inflation expectations for the future are negatively related to gold prices. Nevertheless, the economic policy uncertainty index (EPU) is positively related to gold prices. Beckmann *et al.* (2019) explain these controversial results by explaining that the EPU index is measured based on the newspaper coverage news, while, in the other hand, the macroeconomic uncertainty is related to the incapability of forecasting how the macroeconomic aggregates will evolve. Ultimately, gold is negatively related to the EPU index mainly because this index represents potential bad news that arrive to the markets and directly influence investors decisions. Nevertheless, gold does not seem to be able to protect against the unpredictable.

Besides reacting to inflation and uncertainty, gold prices also react to central banks announcements as any other financial asset. Zhu *et al.* (2018) state that gold prices reacted positively to Fed's Quantitive Easing (QE) announcements. Elfakhani *et al.* (2009) concluded that gold prices in the 90's was determined by some specific variables, specifically the US stock market, the value of the US dollar and central banks activities.

In order to conclude the literature review, there are some recent reports that study gold's inability to serve as a hedge. Gomis-Porqueras *et al.* (2022), for instances, concluded that gold has not lived to its expectations during the Covid-19 crisis, namely gold "*exhibited weak safe haven properties during the Covid-19 crisis*". This is a noteworthy conclusion, as the unexpected fall in gold prices occurred even as inflation reached double digits in both the Eurozone and on the United States.

Based on this literate review it is perceptible that gold prices seem to be influenced by several different determinants. The first determinant analyzed in this literature review was the US dollar. There are several studies pointing to a negative relationship between the US dollar value and gold prices, namely Capie *et al.* (2005), Bukowski (2016), Elfakhani *et al.* (2009), Qian *et al.* (2019), Chiang (2022), Zhu *et al.* (2018) and Gomis-Porqueras *et al.* (2022).

Second, this literature review accessed the connection between stock/bond indices and the yellow metal prices. In this regard, there seems to be no linear relation between gold and stocks or bonds. The conclusions drawn by the authors are slightly distinct due to factors such as the time period considered in their sample and the specific stock/bond indices utilized.

The third determinant considered as capable of influencing gold prices was the region. Once stock indices from different countries can have shown different relations to gold prices, it makes sense to analyze how gold tends to perform as safe haven in different parts of the globe. The main conclusion reached on this subject was that gold performs better as a safe haven in developed markets (Baur and McDermott, 2010).

Fourth, it was scrutinized the relation between inflation and gold prices. The studies reviewed in this literature review consider the money supply (Murach, 2019) and oil prices pressures (Bukowski, 2016), (Apergis *et al.*,2019) which are considered influential in generating inflation. In the inflation-gold prices relation there is some consensus regarding the negative relationship between inflation and gold. Nevertheless, during the last decade, where inflation was relatively low and stable, gold prices sensibility to inflation seemed to decrease as stated by Zhu *et al.* (2018), Elfakhani *et al.* (2009) and Valadkhani *et al.* (2022).

Fifth, the behavior of gold prices against real interest rates was examined. In this topic there seems to be little consensus. Apergis *et al.* (2019) concludes that real interest rates seem to have a positive causality on gold prices, as for other authors such as Lawrence (2003, as cited in Apergis *et. al*, 2019), the relation between gold and real interest rates is not statistically significant.

Finally, the sixth main determinant of gold prices reviewed was the uncertainty measures such as the VIX, SKEW, GPR, EPU, among others. Regarding this uncertainty measures, there are several studies that infer a positive causality between uncertainty and gold prices. For instances, Baur and Smales (2020) states a positive causality between the GPR index and gold as for Beckmann *et al.* (2019) a positive causality between the EPU index and gold is concluded.

Figure A8 in Appendix summarizes all the authors referenced in the literature review above, regarding the gold price determinants.

3. DATASET AND HYPOTHESES

The dataset used in this econometric study corresponds to monthly data covering the period between 01-01-1990 to 01-03-2023, which corresponds to a total of 399 observations for each variable. Once inflation rates and real interest rates for both countries are measured in monthly terms, the frequency of the data employed could not be higher.

Data respecting the volatility index (VIX) is only available from 01-01-1990 and this is the main reason for the data collected to start at this exact date and not sooner. The values for the real interest rates could be obtained by the difference between the 10-year government bond yield and the current inflation rate, such as Apergis *et al.* (2019) did in his study. Nonetheless, when comparing the values of real interest rates calculated as stated before and the values of real interest rates calculated by the Bundesbank[6] or by the FRED of Cleveland, where both institutions incorporate not only the current inflation rate but also the inflation expectations, the differences are quite significant for some periods. As an example of this, if we consider data regarding the month of September 2022, the value of the real interest rate for the US economy obtained by the difference between the 10-year government bond yield and inflation is -4,71% (= 3,51% - 8,22%), as for the real interest rate calculated by the FED of Cleveland for the same month is 1,20%, which corresponds to a significative difference.

To test if real interest rates have asymmetric effects on gold prices, this study incorporates the real interest rates from the German and United Sates retrieved from the Bundesbank and the FRED of Cleveland, respectively.

To measure the impact that stock markets movements might have on gold prices it is used the monthly average price of S&P 500 index. The S&P 500 is globally considered the most important stock index, capable of identifying recessionary movements in the US that might then affect the rest of the World. As considered by Baur and McDermott (2016), the S&P 500 index is a global stock index, such as the MSCI World index.

Concerning uncertainty, this dissertation will incorporate several measures of uncertainty, such as Economic Policy Uncertainty[7] (EPU) for the United States, the Global Geopolitical Risk index calculated by Dario Caldara and Matteo Iacoviello (Caldara and Iacoviello, 2022),

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[6] Based on the average yield to maturity of German Government Bonds (10 years maturity) and weighted inflation rates (Consensus Forecast).

[7] "The Baker, Bloom and Davis daily news-based Economic Policy Uncertainty Index is based on newspaper archives from Access World New's NewsBank service. The index is constructed based on the number of articles that contain at least one term from each of 3 sets of categories. The first set is economic or economy. The second is uncertain or uncertainty. The third set is legislation or deficit or regulation or congress or federal reserve or white house" (Bloomberg).

and the volatility index (VIX). Both the EPU index and thee VIX index were retrieved from the Bloomberg, as for the GPR index, this was obtained from Dario Caldara and Matteo Iacoviello website.

Finally, this econometric study will also include a US dollar index[8], once gold is mostly quoted in US dollars and because, as seen before, the US dollar might function as a safe haven against the precious yellow metal.

In order to facilitate the treatment of this data, a logarithm was applied to all variables. Because some variables had negative values in the period sample considered, such as the US and German inflation, and the US and German real interest rates, a constant was added to all observations of the corresponding variables so that the minimum value was greater than zero, and the log could be applied. The constant values added to each variable were: 2.2 for the US inflation, 0.6 for the German inflation, 0.41 for the US real interest rate and, finally, 2.40 for the German real interest rate.

Table 2 shows the correlation coefficients between all logged variables considered in this econometric study. Based on Table 2, we can observe that seven independent variables are statistically significant in terms of correlation with gold prices, more precisely: the S&P 500 index, US real interest rates, DE real interest rates, the American Dollar index, US inflation, German inflation and the EPU index. Interestingly, although gold is assumed to be a safe haven against inflation, there seems to be a much higher and negative correlation between gold prices and real interest rates, from both economies considered, than between gold prices and inflation. A more illustrated representation of the correlation coefficients matrix can be seen in Figure A9 in the Appendix, where the color scale represents the different degrees of correlation among variables.

It is important that the correlation among variables is not to high, otherwise, the model might suffer from multicollinearity. The highest correlation coefficient among variables corresponds to the correlation coefficient between German real interest rates and the S&P 500 index (-0.809). According to the Greene criteria (Greene, 2003) there is multicollinearity if the coefficient correlation is above 0.95, which is not the case. In this sense, and based on the Greene criteria, it is assured that the multicollinearity is not a problem on this dataset.

[8] The U.S. Dollar index (USDX) corresponds to a measure of the value of the USD. The USDX does this by averaging a basket of foreign currencies against the US dollar. The ICE (Intercontinental Exchange) calculates this by using the rates provided by 500 banks. The basket of foreign currencies is composed by: Euro (EUR), Japanese yen (JPY), Canadian dollar (CAD), British Pound (GBP), Swedish Krona (SEK) and the Swiss Franc (CHF).

Table 2: Correlation coefficients between variables

	US_inflation_YoY	DE_inflation_YoY	S&P500	US_real	DE_real	Gold	Dollar_index	EPU	GPR	VIX
US_inflation_YoY	1									
DE_inflation_YoY	0.627***	1								
S&P500	-0.055	-0.188***	1							
US_real	0.238***	0.407***	-0.662***	1						
DE_real	0.105*	0.24***	-0.809***	0.806***	1					
Gold	-0.126*	-0.114*	0.712***	-0.786***	-0.784***	1				
Dollar_index	0.073	-0.003	0.211***	0.151**	-0.121*	-0.308***	1			
EPU	-0.035	-0.003	0.079	-0.281***	-0.237***	0.26***	0.001	1		
GPR	0.138**	0.166***	-0.017	0.036	-0.008	0.034	0.084	0.082	1	
VIX	-0.089	-0.13**	0.066	-0.108*	-0.022	-0.003	0.181***	0.331***	-0.044	1

Note: *** indicates statistical significance at 1% level, ** indicates statistical significance at 5% level and * indicates statistical significance at 10% level.

The following Table 3 shows the descriptive statistics of all variables used.

Table 3: The descriptive statistics

	Unit	Measure	Mean	Standard Deviation	Skewness	Kurtosis
US_inflation_YoY	Year on Year % change	Logarithmic Form	0.660	0.175	-2.848	22.463
DE_inflation_YoY	Year on Year % change	Logarithmic Form	0.336	0.296	-3.373	29.696
S&P500	Monthly average price	Logarithmic Form	3.090	0.289	-0.126	-0.513
US_real	Monthly percentage	Logarithmic Form	0.232	0.371	-1.848	7.739
DE_real	Monthly percentage	Logarithmic Form	0.461	0.433	-1.476	1.889
Gold	Monthly average price	Logarithmic Form	2.828	0.299	0.126	-1.604
Dollar_index	USD index spot	Logarithmic Form	1.960	0.047	0.236	-0.267
EPU	Index	Logarithmic Form	1.970	0.284	-0.110	-0.222
GPR	Index	Logarithmic Form	1.970	0.158	1.152	3.562
VIX	Index	Logarithmic Form	1.269	0.149	0.527	-0.037

To find out which econometric model would more precisely fit the data, it was assessed the existence of a unit root for all the variables. Before proceeding with the unit root tests, a linearity test was primarily conducted, namely the Harvey and Leybourne (2007) linearity test. Results of the Harvey and Leybourne test can be seen in Table 4. The results of the Harvey and Leybourne (2007) test indicate that the United States and German inflation, the US and German real interest rates, the EPU, GPR and VIX indeces exhibit evidence of non-linearity behavior once the null hypothesis of linearity is rejected at the 10% significance level. The remaining variables, namely the S&P 500 index, gold prices and the US dollar index show evidence of linearity because the null hypothesis is not rejected at the traditional significance levels.

Table 4: The Harvey and Leybourne (2007) test

	RSS0	RSS1	WT	| DF |	WT* (1%)	WT* (5%)	WT* (10%)
US_inflation_YoY	1.223	2.237	331.059	4.499	316.426	314.757	313.821
DE_inflation_YoY	11.425	12.375	33.162	4.524	31.704	31.538	31.445
S&P500	0.525	0.525	0.152	1.327	0.130	0.128	0.126
US_real	4.614	6.238	140.455	3.580	132.698	131.818	131.326
DE_real	3.215	4.272	131.275	2.082	119.055	117.702	116.946
Gold	0.448	0.458	8.409	0.497	5.585	5.324	5.182
Dollar_index	0.033	0.034	7.347	2.187	6.694	6.622	6.581
EPU	24.350	24.941	9.673	8.750	9.451	9.425	9.410
GPR	4.118	4.277	15.429	6.308	14.940	14.884	14.852
VIX	2.618	2.680	9.422	4.992	9.045	9.002	8.978

Note: Critical values for the Harvey and Leybourne (2007) test are 13.3, 9.49, and 7.78 at the level of 1%, 5%, and 10%, respectively. Source: Authors' calculations based on Harvey and Leybourne (2007).

Then, after classifying each variable as linear or nonlinear, different unit root tests were applied, correspondingly. For the variables identified as linear, the Ng and Perron (2001) test was applied. For all the remaining variables, the ones identified as nonlinear, the test used was Kapetanios *et al.* (2003). The software used to calculate the Ng and Perron (2001) test was EViews, version 11.

Table 5: The Ng and Perron (2001) unit root test

Variable	Level (intercept)				First difference (intercept)			
	MZα	MZt	MSB	MPT	MZα	MZt	MSB	MPT
S&P500	1.318	1.886	1.432	145.126	-20.756***	-3.221***	0.155***	1.181***
Gold	1.163	1.158	0.995	71.624	-188.639***	-9.709***	0.051***	0.134***
Dollar_index	-11.889**	-2.387**	0.201**	2.265**	-161.699***	-8.989***	0.056***	0.155***

Variable	Level (trend and intercept)				First difference (trend and intercept)			
	MZα	MZt	MSB	MPT	MZα	MZt	MSB	MPT
S&P500	-5.941	-1.724	0.290	15.339	-41.852***	-4.548***	0.109***	2.318***
Gold	-1.908	-0.948	0.497	45.848	-192.085***	-9.794***	0.051***	0.492***
Dollar_index	-11.978	-2.393	0.200	7.906	-173.213***	-9.306***	0.054***	0.527***

Note: *** indicates statistical significance at 1% level, ** indicates statistical significance at 5% level, and * indicates statistical significance at 10% level. For all the nonlinear variables identified, the results of the Kapetanios *et al.* (2003) test are shown in table 5.

The results from the Ng and Perron (2001) unit root test, shown in Table 5, indicate that the S&P 500 index, gold prices and the US dollar index are non-stationary in levels and stationary in first differences.

According to the Kapetanios *et al.* (2003), displayed on Table 6, all variables considered are stationary in levels, except for the GPR index. This index does not become stationary in the first or second differences. In order to have solid results regarding the stationary tests, the Clemente *et al.* (1998) will then confirm if the GPR index is or not stationary.

Table 6: Kapetanios *et al.* (2003) unit root test

Variable	Level	First difference
US_inflation_YoY	0.0	0
DE_inflation_YoY	0.0	0
US_real	0.0	0
DE_real	0.0	0
EPU	0.0	0.01
GPR	0.852	1
VIX	0.002	0.989

P-values of the Kapetanios et al. (2003)

Note: The number of lags was defined according to the SIC criteria[9].

To reinforce the conclusions obtained from this unit root test another unit root test will be applied, namely one that accounts for possible structural breaks, the Clemente *et al.* (1998).

The Clemente *et al.* (1998) unit root test, which considers the possible existence of two unknown structural breaks, was applied to all variables considered. The existence of structural breaks could invalidate the results obtained in the two previous unit root tests. The software used to calculate the Kapetanios *et al.* (2003) unit root test was Stata, version 17.0, command "kssur".

Notwithstanding the fact that structural breaks were identified for all variables considered, the null hypothesis of a unit root cannot be rejected at the conventional significance levels, when variables are measured in levels, for the vast majority of variables. The variables for which the null hypothesis can be reject in the case of innovative outliers are the US and German inflation, the EPU and GPR index.

[9] In agreement with Liew (2004), the number of lags considered in the Kapetanios *et al.* (2003) unit root test was the Schwarz Information Criterion (SIC) and not the Akaike's Information Criteria (AIC). The AIC information criteria is better for small samples (60 observations or less). Because this econometric study has a sample size of 399 observations, the information criteria considered was the SIC.

The GPR index, when measured in first differences, becomes stationary in the additive and innovative outliers. This result dissipates the uncommon results obtained in the Kapetanios *et al.* (2003) for this variable.

Even though the results are somewhat contradictory in some cases, the main conclusion to be taken is that all unit root tests conducted point to some variables being stationary in levels and others being stationary in the first differences and no variables are integrated of order two.

The results of the Clemente *et al.* (1998) unit root test can be seen in Table 7. The software used to calculate Clemente *et al.* (1998) unit root test was Stata, version 17.0.

Table 7: Clemente *et al.* (1998) test

Variable	Level (intercept)	
	Additive Outliers Breaks, *t*-statistic	Innovative Outliers Breaks, *t*-statistic
US_inflation_YoY	2009m2***, 2009m5***, -2.864	2008m9***, 2009m6***, -6.936
DE_inflation_YoY	2009m5***, 2020m5***, -2.665	2020m5*** , 2020m9***, -8.165
S&P500	1996m8***, 2013m8***, -3.668	1995m7***, 2012m7***, -3.839
US_real	2008m9***, 2020m6***, -2.011	2008m10***, 2020m1, -3.236
DE_real	2011m10***, 2019m3***, -2.759	2011m4***, 2019m3, -3.034
Gold	2006m1***, 2009m12***, -3.830	2005m7***, 2008m12**, -4.016
Dollar_index	2004m3***, 2015m4***, -3.805	1996m10***, 2002m1***, -3.392
EPU	2007m5***, 2019m9***, -4.784	2007m6**, 2019m10**, -8.170
GPR	2001m6***, 2004m7***, -3.418	2001m7***, 2003m2***, -10.000
VIX	1996m4***, 2011m7***, -5.849	1995m12**, 2011m8, -3.827
Variable	**First differences**	
	Additive Outliers Breaks, *t*-statistic	**Innovative Outliers Breaks, *t*-statistic**
US_inflation_YoY	2009m5***, 2009m12***, -5.976	2009m6***, 2009m12***, -8.381
DE_inflation_YoY	2009m5, 2020m5, -7.649	2009m6, 2020m6***, -17.020
S&P500	2000m8, 2008m9, -5.968	2000m9**, 2008m10*, -10.937
US_real	2020m1**, 2020m6**, -5.249	2020m2***, 2020m7***, -14.748
DE_real	2020m1*, 2020m10***, -6.769	2020m2, 2020m11***, -9.773
Gold	2001m7*, 2008m3, -6.049	2002m1***, 2008m4*, -20.533
Dollar_index	2002m3**, 2008m8**, -9.733	2002m4**, 2008m9**, -9.867
EPU	1995m10, 2008m7, -8.613	1995m11, 2008m8, -9.164
GPR	2001m6***, 2001m10***, -9.791	2001m7***, 2001m11***, -12.053
VIX	2008m8, 2019m12, -6.816	2019m12***, 2020m2***, -12.122

Note: Critical values for the Clemente *et al.* (1998) unit root test with two structural breaks are -5.96, -5.49, and -5.24 at the level of 1%, 5%, and 10%, respectively, *** indicates statistical significance at 1% level, ** indicates statistical significance at 5% level, and * indicates statistical significance at 10% level.

4. ECONOMETRIC MODEL

The econometric model implemented in this study corresponds to the Nonlinear ARDL (NARDL) estimator developed by Shin *et al.* (2014), which corresponds to a development of the ARDL model proposed by Pesaran (1997), Pesaran and Shin (1999) and Pesaran *et al.* (2001). The reason to apply a NARDL estimator in this paper is threefold: first, the NARDL provides robust estimations for a mixture of variables integrated of order zero I(0) and of order one I(1). As seen before, the stationary tests results are not completely consistent, and therefore the application of the NARDL could mitigate this issue.

Second, based on all the stationary tests conducted, none of the variables is integrated of order two I(2), which is another condition that must verify in order for a NARDL model to be estimated.

Third, gold prices appear to exhibit some short- and long-term asymmetric responses to some of the independent variables considered in this model. For instances, Bilgin *et al.* (2018) also applied a NARDL estimator to study the asymmetric behavior of gold prices with special focus on some uncertainty measures, such as VIX, SKEW, PC and global EPU indexes. Once the asymmetric effects of these uncertainty measures on gold prices have already been object of study, they will not enter the econometric model as asymmetric variables. Besides this, it was only possible to study the possible existence of three explanatory variables due to the size of the dataset.

The NARDL estimator also as the benefit of allowing the use of variables in levels, without the need to take the first differences, which facilitates the economic interpretation of the results. The software used to acquire the estimates was EViews, version 11.

The estimation of a NARDL model involves generically five steps, being the first step the determination of how many lags to use. Gold prices will be modelled based on its lagged values and also based on the actual and lagged values of the independent variables.

The determination of the appropriate number of lags to incorporate in this model was firstly based on the traditional information criteria.

Table 8 points to the appropriate number of lags being two, based on the FPE, AIC and HQ information criteria. Nonetheless, estimating the model with a maximum of two lags would lead to residuals being serial correlated at the second lag. To obtain residuals serial uncorrelated, the maximum number of lags, for both the dependent and all the independent variables, was then increased to three lags.

Table 8: Values of the information criteria for each lag

Lag	FPE	AIC	SC	HQ
0	3.80E-18	-8.896	-8.784	-8.851
1	4.03E-28	-31.862	-30.522*	-31.331
2	1.67e-28*	-32.743*	-30.175	-31.725*
3	2.03E-28	-32.553	-28.757	-31.048
4	2.10E-28	-32.527	-27.502	-30.535
5	2.27E-28	-32.458	-26.205	-29.979
6	2.59E-28	-32.341	-24.86	-29.376
7	3.28E-28	-32.127	-23.418	-28.675
8	3.73E-28	-32.028	-22.091	-28.089

Note: * indicates the optimal lag order defined by the respective information criteria.

The NARDL model introduced by Shin *et al.* (2014) can be specified in the long run as described in equation 1:

$$log(GP)_t = \alpha_0 + \alpha_1 log(USinf)_t + \alpha_2 log(DEinf)_t + \alpha_3 \log(USint)_t^+ + \alpha_4 \log(USint)_t^- + \alpha_5 log(DEint)_t^+ + \alpha_6 log(DEint)_t^- + \alpha_7 log(SP500)_t + \alpha_8 log(DI)_t^+ + \alpha_9 log(DI)_t^- + \alpha_{10} log(GPR)_t + \alpha_{11} log(VIX)_t + \alpha_{12} log(EPU)_t + \varepsilon_t \quad (1)$$

Where variables GP, USinf, DEinf, USint, DEint, SP500, DI, GPR, VIX and EPU correspond to the monthly average price of gold, US inflation, German inflation, US real interest rate, German real interest rate, the S&P 500 index, the American Dollar index, the Geopolitical Risk index (GPR), the Chicago Board Options Exchange (CBOE) volatility index (VIX) and the Economic Policy Uncertainty index (EPU), respectively. Note that in equation 1, in order to detect possible asymmetric effects of the US and German real interest rates and the dollar index on gold prices, these three variables are decomposed into positive and negative shocks.

To measure the asymmetric impact these variables might have on gold prices in both the short- and long-term, according to Shin *et al.* (2014), equation 1 can then be written as follows, where i = 0, 1, 2 or 3:

$$log(GP)_t = \alpha_0 + \alpha_1 log(USinf)_t + \alpha_2 log(DEinf)_t + \alpha_3 \log(USint)_t^+ + \alpha_4 \log(USint)_t^- + \alpha_5 log(DEint)_t^+ + \alpha_6 log(DEint)_t^- + \alpha_7 log(SP500)_t + \alpha_8 log(DI)_t^+ + \alpha_9 log(DI)_t^- + \alpha_{10} log(GPR)_t + \alpha_{11} log(VIX)_t + \alpha_{12} log(EPU)_t + \sum_{i=0}^{\rho} \gamma_1 \Delta GP_{t-i} + \sum_{i=0}^{\rho} \gamma_2 \Delta USinf_{t-i} + \sum_{i=0}^{\rho} \gamma_3 \Delta DEinf_{t-i} + \sum_{i=0}^{\rho} \gamma_4^+ \Delta USint_{t-i} + \sum_{i=0}^{\rho} \gamma_5^- \Delta USint_{t-i} +$$

$$\sum_{i=0}^{\rho}\gamma_6^{+}\,\Delta DEint_{t-i}+\sum_{i=0}^{\rho}\gamma_7^{-}\,\Delta DEint_{t-i}+\sum_{i=0}^{\rho}\gamma_8\,\Delta SP500_{t-i}+\sum_{i=0}^{\rho}\gamma_9^{+}\,\Delta DI_{t-i}+\sum_{i=0}^{\rho}\gamma_{10}^{-}\,\Delta DI_{t-i}+\sum_{i=0}^{\rho}\gamma_{11}\,\Delta GPR_{t-i}+\sum_{i=0}^{\rho}\gamma_{12}\,\Delta VIX_{t-i}+\sum_{i=0}^{\rho}\gamma_{13}\,\Delta EPU_{t-i}+\varepsilon_t \quad (2)$$

The α_k correspond to the long-term coefficients, γ_k to the short-term coefficients and ε_t is an independent and identically distributed (white noise) disturbance term with a null average and constant variance, and i represents the number of lags (= 0, 1, 2 or 3). The second step corresponds to the examination of the existence or not of a cointegrating relationship among all variables. To test the existence of cointegration, the Bounds test developed by Pesaran *et. al* (2001) is applied.

Table 10: Bounds test

F- statistic	Critical value	Lower Bound	Upper Bound
3.4625	1%	2.07	3.16
	5%	2.33	3.46
	10%	2.84	4.1

Table 9: Diagnostic tests

Diagnostic test	*F*- statistic	*p* Value
Breusch-Godfrey	0.164	0.849
Jarque-Bera	84.315	0.000
ARCH	1.327	0.250
Ramsey's RESET	5.775	0.017

The results of the Bounds test procedure are represented in Table 9. The *F*- Statistic value (3.4625) is greater than the Upper Bound values for a significance level of 10% and 5%, which means that there is evidence of the variables being cointegrated.

The third step in the estimation of a NARDL consists in the analysis of several diagnostic tests to confirm that the estimates are reliable. These diagnostic tests serve to evaluate if the residuals are not serially correlated, normally distributed, homoscedastic, and well specified in its functional form.

Table 10 demonstrates the diagnostic tests that result from the NARDL estimation. The Breusch-Godfrey test confirms that the residuals are serial uncorrelated. The Jarque-Bera does not confirm that the residuals are normally distributed, nevertheless, given that the sample used in this econometric study largely exceeds 30 observations, residuals are indeed normal, according to the central limit theorem. Plus, as stated by Hendry and Juselius (2000), the normality hypotheses is commonly not satisfied in economic applications, but this does not compromise the global robustness of estimates or the respective statistical inference.

The ARCH test indicates that residuals are homoscedastic. Lastly, the Ramsey´s RESET test confirms, at a 1% significance level, that the econometric model is well specified in its functional form. Although the Ramsey’s RESET test does not strongly confirm the well specification of the NARDL model, this is not to be considered a problem, once the Ramsey's RESET test should be applied to estimates generated by the OLS estimator (Agung, 2009).

The CUMSUM test (see Figure A10 in the Appendix) supports the inexistence of structural breaks, after one structural break was considered, namely in date 2005M08. This structural break was first identified using EViews 11 Multiple Breakpoint test. Using then the date given by this last test, two more tests were conducted to confirm the existence of a structural break at 2005M08.

Table 11: Stability Diagnostics

Stability Diagnostics	*F*- statistic	*p* Value
Chow Breakpoint test	2.509	0.000
Quandt-Andrews Breakpoint test*	67.756	0.001

The results from these two structural break tests are exhibited in Table 11. In consideration of the results obtained from both tests, a dummy was considered as an exogeneous variable in the estimation of this NARDL. This dummy assumed the value of 1 from date 01/08/2005 onwards.

5. RESULTS AND DISCUSSION

The fourth step of this NARDL estimation is the presentation of the short and long-term estimates[10].

Table 12 illustrates the long-term estimates for the yellow metal prices. At the conventional significance levels, the variables that are statistically significant correspond to the German and American inflation rates, negative changes of the German real interest rate, negative impacts of the Dollar index and the S&P 500 index. The results seem to suggest that, in the long-term, negative changes in the real interest rate of one the strongest and safest economies in the world, tends to influence the price of gold, namely if real interest rates in Germany increases by 1%, gold prices tend to fall by -0.235%, in the long-term. Nevertheless, positive changes in the German real interest rate seem to have no impact on gold prices. This baseline evidence is supported through the dynamic multiplier graph (see Figure A11 in the Appendix), where it is visible that negative changes in the DE real variable exert a much more significant impact on the dependent variable.

The US inflation coefficient has the expected sign and is in accordance with past literature regarding this topic. More precisely, if US monthly inflation increases by 1%, gold prices will increase by 0.226%. This outcome clearly reflects the gold capability to defend investors against inflation, as also concluded by other authors such as Murach (2019), Bukowski (2016), Apergis *et al.* (2019) and Białkowski *et al.* (2015).

S&P500 index also has a negative coefficient, which illustrates that gold has a propensity to move contrarily to what is happening in stock markets. Furthermore, this outcome too supports the safe heaven characteristic of gold and meets the results obtained from Bukowski (2016) and Qian *et al.* (2019). Both authors concluded that there is a negative relation between the S&P 500 index and gold prices. Furthermore, Baur and Lucey (2010) stated that precious metal acts as a safe haven for stocks.

The US Dollar, as suggested by other papers, can act as a safe haven against gold itself. This function of the American dollar is also supported with the result here obtained and is perceptible through the negative coefficient of the negative changes on the US dollar index (-2.11). This means that if the US dollar loses value, gold prices, on the other hand, will tend to increase. Authors such as Bukowski (2016), Elfakhani *et al*. (2009), Qian *et al.* (2019), Chiang

[10] To accommodate the strong trending behaviour of variables (Figure A12), estimates were estimated based on case number five, more specifically considering an unrestricted constant and unrestricted linear trend.

(2022), Zhu *et al*. (2018) and Gomis-Porqueras *et al.* (2022) all find statistical evidence of a negative interdependence between gold prices and the US dollar exchange rate, which is in line with the results obtained. The dynamic multiplier graph of the US dollar index also sustains this conclusion. In Figure A11 in the Appendix, it can be seen that the negative multiplier of the American dollar exerts a higher impact on gold prices when compared to the positive multiplier.

To be notice that only negative changes in the US Dollar index are statistically significant. The same happens with German real interest rates, which indicates that gold prices and gold itself tend to be more demanded when negative changes occur. This reinforces once again the idea that gold is continuously traded as a financial instrument, and in this regard tends to react more to negative than to positive changes or news.

Positive and negative changes in the American real interest rate are not statistically significant in the long-term, what points to the inexistence of asymmetric effects of this variable on gold prices. This conclusion is also corroborated by the dynamic multiplier graph of this variable (see Figure A11 in the Appendix), where, contrarily to what happens with the German real interest rate and the US dollar index, the positive and negative multiplier of the US real interest rate seem to annulate one another leading to no asymmetric impact on gold prices.

Table 12: Long-term estimates

Variable	Coefficient	Standard error	T-statistic
$DE\ inflation_t$	-0.101**	0.043	-2.322
$DE\ real_t^+$	-0.089	0.0955	-0.9306
$DE\ real_t^-$	-0.235**	0.114	-2.057
$Dollar\ index_t^+$	0.874	0.741	1.179
$Dollar\ index_t^-$	-2.11***	0.741	-2.850
EPU_t	0.05	0.041	1.203
GPR_t	-0.053	0.079	-0.678
$S\&P500_t$	-0.597***	0.190	-3.145
$US\ inflation_t$	0.226***	0.0709	3.1805
$US\ real_t^+$	0.023	0.112	0.203
$US\ real_t^-$	0.082	0.109	0.750
VIX_t	0.017	0.101	0.169

Note: *** indicates statistical significance at 1% level, ** indicates statistical significance at 5% level, and * indicates statistical significance at 10% level.

An unexpected outcome is that none of the uncertainty variables considered are statistically significant in the long-term. This conclusion could be explained by the fact the yellow metal prices is mostly influenced by negative and short-lived events as stated by Baur and McDermott (2010). This could explain why gold has no long memory to this uncertainty measures.

Table 13 contains the short-term estimates for gold prices. At the traditional significance levels, the error correction term (ECT) is statistically significant and exhibits a negative coefficient that lies between -2 and 0 (-0.0656). The fact that the ECT is statistically significant and lies between -2 and 0 confirms the convergence of the model to the long-term equilibrium, even if there is any shock in the short-term. The speed of adjustment, in case there is a short-term shock, is corrected within a month by approximately 7%.

As represented in Table 13, gold prices are statistically significant at the traditional significance levels in *t*-1 and *t*-2. The fact that gold prices today depend on or are influenced by gold prices one and two months ago, suggests that there seems to exist some inertia related to gold prices. This result can be viewed as a stylized fact in financial markets, as also acknowledged by Pinho e Barradas (2021).

The US real interest rate appears to have asymmetric effects on gold prices, once both the positive (in *t*) and the negative (in *t*-1) changes in the US real interest rate are statistically significant. Nonetheless, both positive and negative changes have a negative and identical impact on gold prices. The negative change of US real interest rates on gold prices is only statistically significant, at the traditional significance levels, in period *t*-1. This result is in congruence with the outcome obtained by Apergis *et al.* (2019), namely the negative and significant relationship between the lagged value of real interest rates and gold.

Other variable that has asymmetric impacts on gold prices is the American dollar index. For positive changes in the value of the dollar index in the current period (*t*) and two months ago (*t*-2), there is statistical evidence of a negative impact on gold prices.

In the short-term, one uncertainty measure is statistically significant, namely the volatility index (VIX). If the VIX index increases by 1%, gold prices will rise by 0.015%, meaning that there will be a higher demand and consequent pressure on gold prices in times of uncertainty.

Table 14 shows the economic effects of the long-term estimates that were proven to be statistically significant, in the long-term, in order to assess the contribution of each one to the evolution the yellow metal prices in the period from 02-1990 to 03-2023. The behavior of gold prices in this period can be divided into three different parts. From 1990 to 2005 gold prices exhibited a very constant and stable path. Then, from 2005 to year 2014, gold prices increased abruptly. From 2014 until the end of the period gold prices remained constant for a few years and increased aggressively once more. In this sense, the economic effect is carried out for the three specific periods previously identified and then for the full period (see figure A12 in the Appendix).

Table 13: Short-term estimates

Variable	Coefficient	Standard error	*T*-statistic
$\Delta Gold_{t-1}$	0.087*	0.047	1.840
$\Delta Gold_{t-2}$	-0.141***	0.045	-3.101
$\Delta Dollar\ index_t^+$	-0.468***	0.153	-3.067
$\Delta Dollar\ index_{t-1}^+$	-0.132	0.159	-0.828
$\Delta Dollar\ index_{t-2}^+$	-0.417***	0.146	-2.860
$\Delta Dollar\ index_t^-$	-0.909***	0.156	-5.830
$\Delta Dollar\ index_{t-1}^-$	0.515***	0.163	3.164
ΔGPR_t	0.011*	0.006	1.797
$\Delta US\ real_t^+$	-0.034***	0.012	-2.821
$\Delta US\ real_t^-$	0.009	0.009	1.085
$\Delta US\ real_{t-1}^-$	-0.032***	0.012	-2.780
ΔVIX_t	0.015**	0.007	1.980
$Dummy_{2005M08}$	0.017***	0.003	5.278
ΔECT_t	-0.0656***	0.010	-6.818
R-squared = 0.319		Adjusted R-squared = 0.292	

Note: Δ stands for the operator of first differences, *** indicates statistical significance at 1% level, ** indicates statistical significance at 5% level, and * indicates statistical significance at 10% level.

For these four periods, the estimates considered are the same as the estimates determined in the long-term estimates, once the stability of the model was already proven and, consequently, the estimates remain stable over period as proved before through CUMSUM test.

In the period form 01-02-1990 to 01-08-2005 the variable that contributed mostly in negative terms for the gold price evolution was the S&P 500 index. In the other hand, the variables that annulated this negative impact were the German inflation, the negative changes in the German real interest rate and, finally, the US dollar index.

The second period (from 01-09-2005 to 01-02-2014), the variable, from the set of variables statistically significant in the long-term for this model, that contributed the most to the steep increase of gold prices was the negative changes in the German real interest rates and the US dollar index. Once more, the impact that German real interest rates have on gold prices is here reflected.

The third period, where gold prices remained constant for a few years and then increased significantly from 2018 on, the variable in our model that mostly sustain this increase is the US inflation.

Finally, considering the full period, the variables that can be considered the main drivers of gold prices are the S&P 500 index (-0.256%) in negative terms, and the negative shocks in the DE real interest rate contributed the most in positive terms (0.136%).

Table 14: The economic effects of long-run estimates

Period	Variable	Long-term coefficient	Actual cumulative change	Economic effect
Gold price stability 02/1990 - 08/2005	DE inflation_t	-0.101	-0.341	0.034
	DE real_t^-	-0.235	-0.272	0.064
	Dollar index_t^-	-2.111	-0.012	0.026
	$\text{S\&P500}_t$	-0.597	0.220	-0.131
	US inflation_t	0.226	-0.122	-0.028
Gold price first steep increase 09/2005 - 02/2014	DE inflation_t	-0.101	-0.329	0.033
	DE real_t^-	-0.235	-0.425	0.100
	Dollar index_t^-	-2.111	-0.019	0.040
	$\text{S\&P500}_t$	-0.597	0.055	-0.033
	US inflation_t	0.226	-0.382	-0.086
Gold price second steep increase 03/2014 - 03/2023	DE inflation_t	-0.101	3.030	-0.306
	DE real_t^-	-0.235	0.184	-0.043
	Dollar index_t^-	-2.111	0.058	-0.122
	$\text{S\&P500}_t$	-0.597	0.100	-0.060
	US inflation_t	0.226	0.509	0.115
Full period 02/1990 - 03/2023	DE inflation_t	-0.101	0.733	-0.074
	DE real_t^-	-0.235	-0.578	0.136
	Dollar index_t^-	-2.111	0.024	-0.051
	$\text{S\&P500}_t$	-0.597	0.429	-0.256
	US inflation_t	0.226	-0.020	-0.005

Note: The actual cumulative change corresponds to the growth rate of the correspondent variable during the period considered. The economic effect is then calculated trough the multiplication between the long-term coefficient and the actual cumulative change for each variable.

6. CONCLUSIONS AND POLICY IMPLICATIONS

The vast existing literature regarding gold prices determinants considers a significant amount of different explanatory variables to explain what influences and determines gold prices. Nevertheless, these papers seem to overlook the importance of real interest rates and more precisely German real interest rates.

In this dissertation, the determinants of gold were analyzed, with a special focus on real interest rates, more precisely, real interest rates from two of the safest economies in the world.

Using the nonlinear ARDL model, evidence of asymmetric effects of real interest rates on gold prices was found.

Negative shocks in the German real interest rate exert a negative impact on gold prices, in the long-term. As for the short-term, both negative and positive changes in the US real interest rates impact negatively gold prices. In the case of negative changes in the US real interest rates, only the lagged value (t-1) proved to be statistically significant.

Other than real interest rates, also the American US dollar has proven to have asymmetric effects on the noble metal prices. In the short-term, positive changes in the USD index impact negatively gold. In terms of negative changes in the American dollar index, results are not so linear. In the current period (t), a negative change in the dollar index leads to a decrease in gold prices, as for a negative change one periods ago (t-1) leads to an increase in gold prices, and in this sense no conclusion can be taken with respect to the short-term.

On the other hand, in the long-term, negative changes in the value of the American currency impact negatively gold prices.

Both, in the short- and long-term, there is statistical evidence of an inverse co-movement between the United States dollar value and gold prices, what corroborates the safe haven property of the dollar against gold, and that a US dollar depreciation tends to lead to a gold appreciation.

The findings of this paper offer a better awareness into practices of portfolio diversification and risk management, since it reaches the conclusion that real interest rates tend to influence gold prices.

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8. APPENDIX

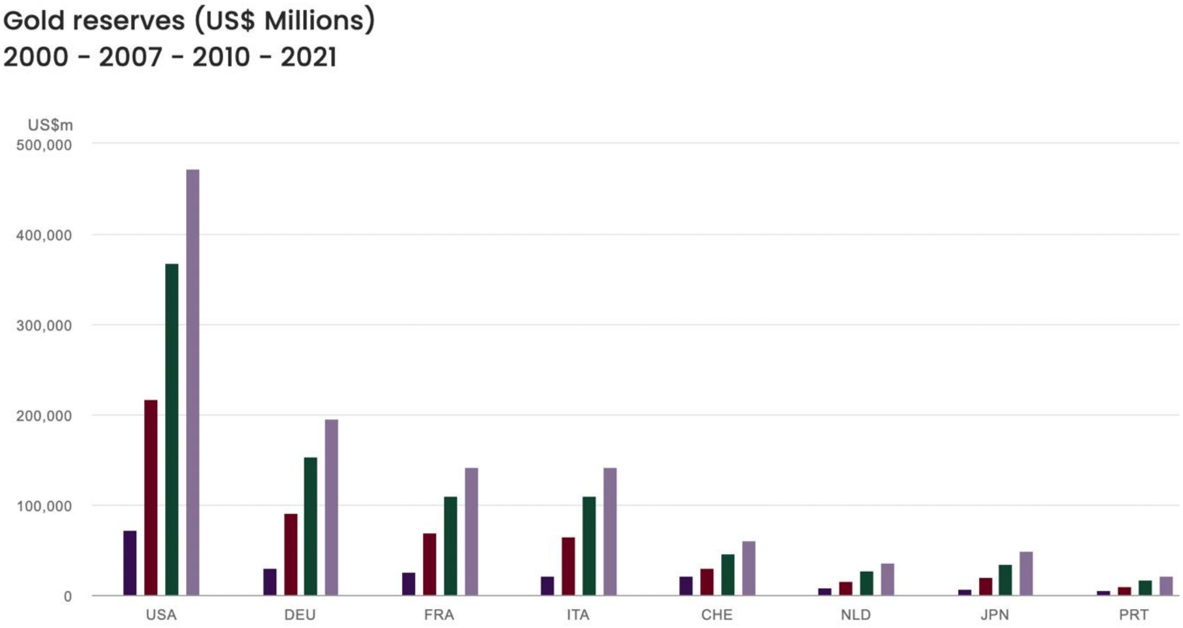

Figure A1: Gold reserves (US$ Millions) in 2000, 2007, 2010 and 2021. First column represents year 2000 and the most to the right the year 2021. Source: World Gold Council

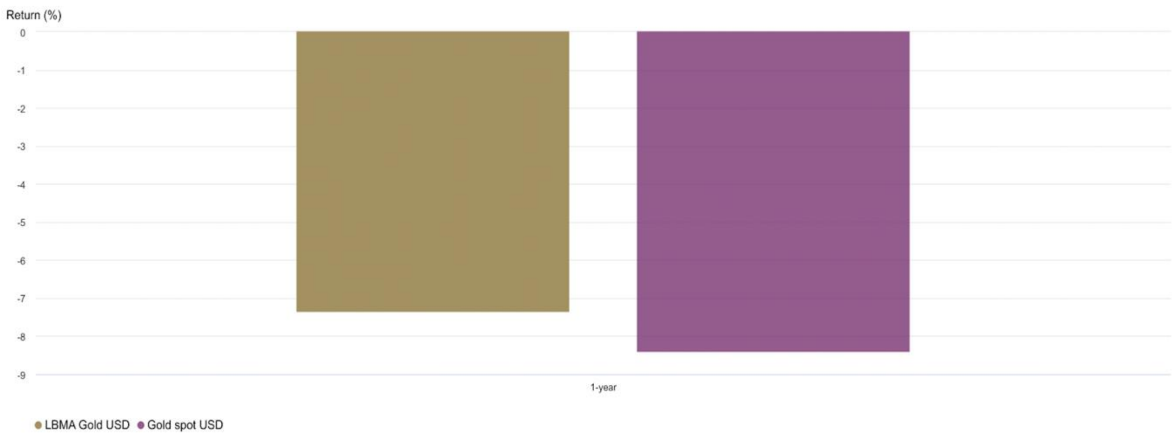

Figure A2: Gold returns year to date (from 01/01/2022 to 26/11/2022), measured in US$/oz. Source: World Gold Council

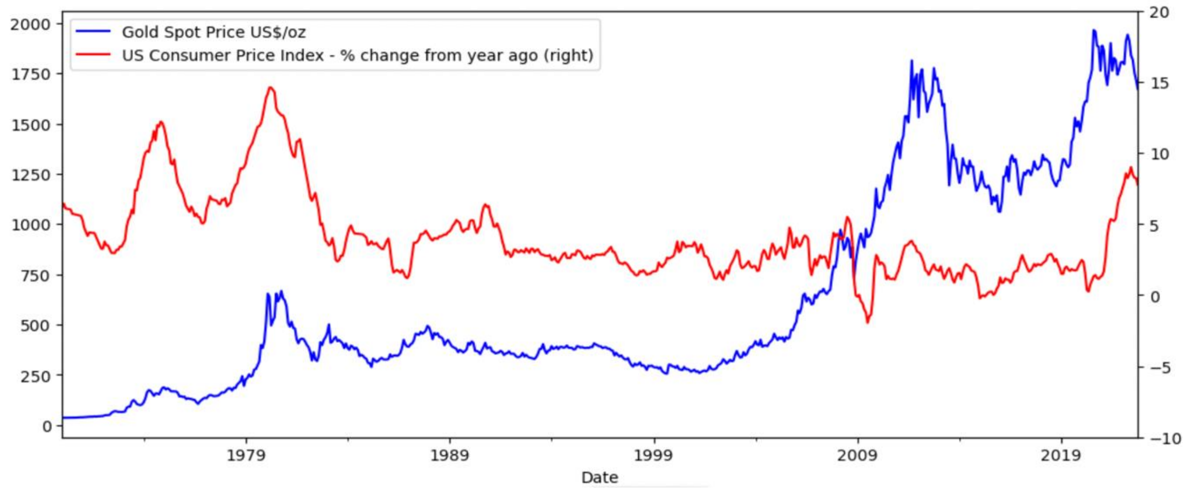

Figure A3: US consumer price index and Gold Spot Prices from January 1970 to October 2022. Data source: World Gold Council and Federal Reserve Bank of St. Louis (FRED).

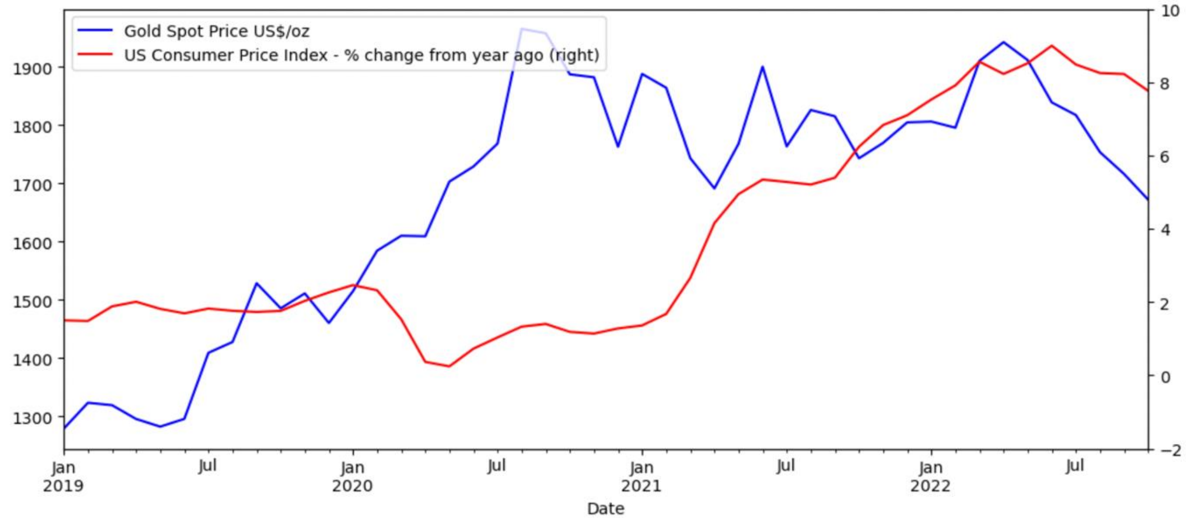

Figure A4: US consumer price index and Gold Spot Prices from January 2020 to October 2022. Data source: World Gold Council and Federal Reserve Bank of St. Louis (FRED).

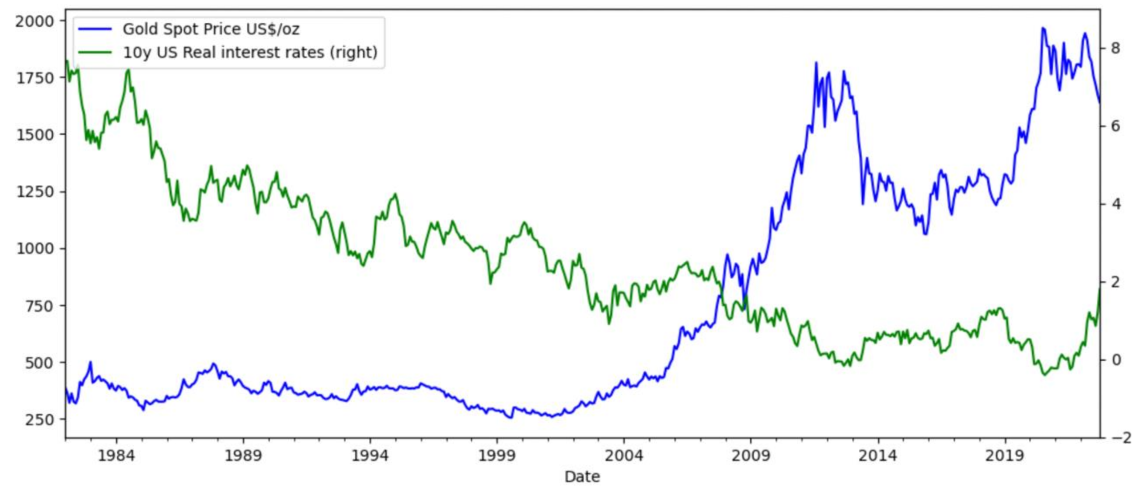

Figure A5: 10-year US Real Interest Rates and Gold Spot Prices from January 1982 to October 2022. Data source: Federal Reserve Bank of St. Louis (FRED) and World Gold Council, respectively.

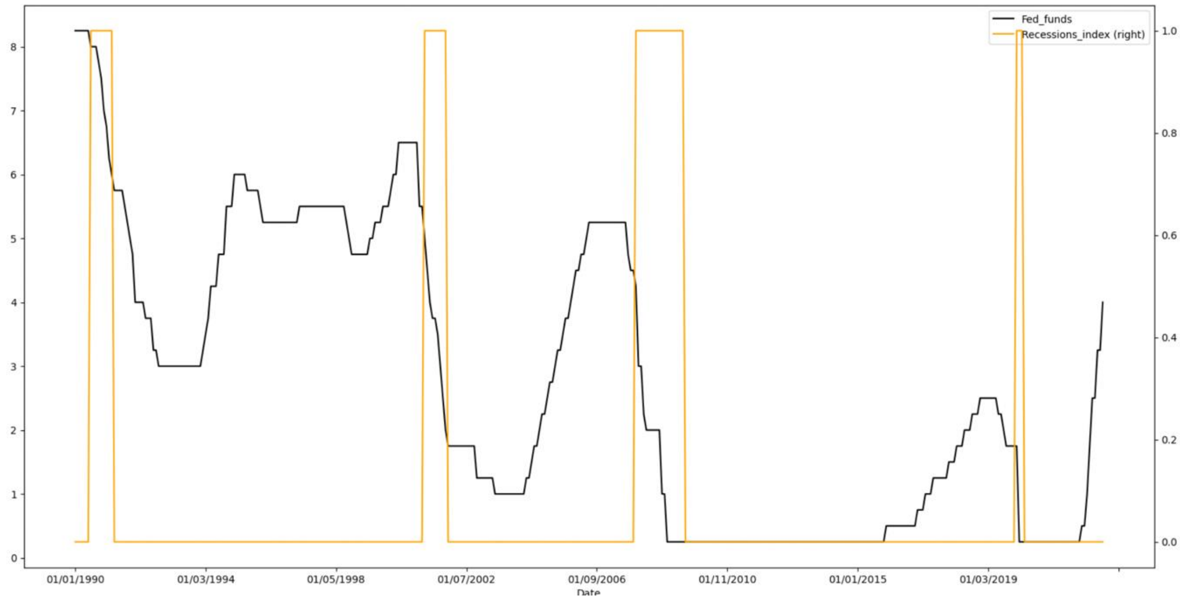

Figure A6: Relationship between the Fed Funds rate and the Recessions index from the US economy. Data source: Bloomberg.

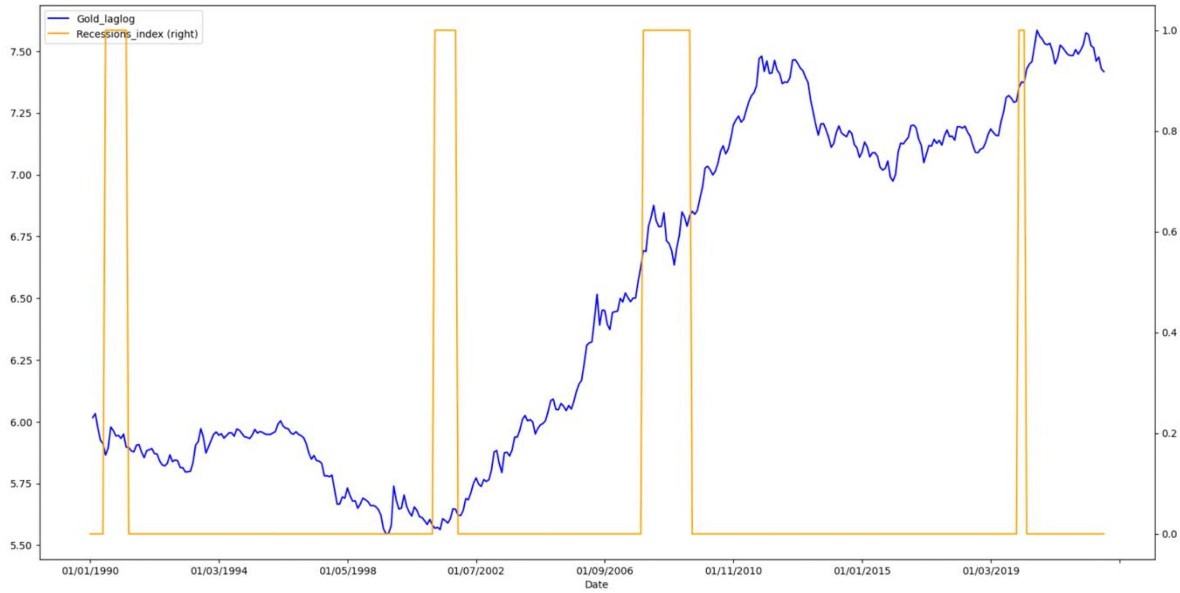

Figure A7: Relationship between gold prices and the US recession index. Data Source: Bloomberg.

Authors	Sample; Estimation Method	Hypotheses/variables tested	Main results
Murach (2019)	Panel data 1980 - 2013 Multivariative cointegration (CVAR)	Real money supply	Positive correlation between gold and inflation.
Chirwa *et al.* (2020)	Time series 12/2018 - 05/2020 Bai and Perron (1995) methodology and ARDL-based error-correction	Lagged gold price Stock indexes Bond indices	Positive correlation with stocks. Negative correlation with bonds.
Elfakhani *et al.* (2009)	Time series 1971 - 2001 Kaufman-Winters (1989)	GNP deflator index, Dollar exchange index, Mine production, Official sector sales, Old gold scrap, Producer hedging instruments, gold fabrication, Bar hoarding and the S&P 500 index	Positive correlation with inflation in the 1980's. Negative correlation with inflation from 1990's.
Bukowski (2016)	Time series 01/1999 - 02/2016 GARCH (0.1)	US/EUR exchange rate, oil prices, US 10-year Treasury bonds, S&P 500 index	Negative correlation with the US/EUR exchange rate, the S&P 500 index and the 10-year US Treasury bonds. Positive correlation with crude oil prices and lagged gold prices.

Apergis *et al.* (2019)	Panel data 1975 - 2016 Markov Switching Vector Error Correction Model (MS-VECM)	Real interest rates, CPI, real GDP, Dollar exchange rates, commodity prices and stock indexes	Positive correlation with real interest rates, oil prices and inflation. Negative correlation with the lagged value of real interest rates.
Qian *et al.* (2019)	Time series 01/2000 – 12/2018 Box–Behnken Design e Design Expert	US dollar index, FED funds rate, CPI, exchange rate, oil prices and S&P500	Positive correlation with inflation. Negative correlation with the US dollar Index, FED funds rate, exchange rate, oil price and S&P500.
Valadkhani *et al.* (2022)	Time Series January 1969 to March 2021 OLS and DLS	CPI and 10-year US Treasury interest rates	Positive correlation with inflation. Negative correlation with the 10-year Treasury interest rate.
Bilgin *et al.* (2018)	Time series 01/1997 – 05/2017 Nonlinear Autoregressive Distributed Lag (NARDL)	VIX, SKEW, EPU, PC (partisan conflict index), real effective exchange rate and crude oil prices	Positive correlation with the EPU index. Negative correlation with the real effective exchange rate.
Chiang (2022)	Panel data 01/1998 – 08/2020 GED-GARCH	Equity financial market volatility, EPU, GPR, CPI, economic growth, exchange rates, effective real exchange rate and lagged gold prices	Positive correlation with the uncertainty variables, CPI and exchange rate. Negative correlation with economic growth.
Zhu *et al.* (2018)	Panel data 01/1985 – 05/2015 Ordinary least squares	Inflation expectations (BEIR), exchange rates, stock market returns, 3-month Treasury bill rates, and QE news (FED, ECB, BoE and BoJ)	Positive correlation with inflation for the UK (1985 to 1997), real exchange rates (UK and US), FED's QE announcements and stock market returns. Insignificant correlation with inflation for the UK (1997–2015) and the US (2003–2015).
Białkowski *et al.* (2015)	Panel data 01/1975 – 06/2013 Markov regime-switching ADF	US dollar effective exchange rate, CPI, MSCI World index, 3-month US Treasury bill rates, spread between PIIGS and Germany	Positive correlation with inflation.
Beckmann *et al.* (2019)	Panel data 1985 to 2014 Copula wavelet approach	Exchange rates against the US dollar, stock and 10-year bond indices, macroeconomic uncertainty and EPU	Positive correlation with stocks and bonds after 2008 and with the EPU index.

			Negative correlation with macroeconomic uncertainty and inflation uncertainty.
Baur and Smales (2019)	Time series 01/1985 – 10/ 2018 Ordinary least squares	GPR, macroeconomic state and market control variables	Positive correlation with geopolitical risk.
Batten *et al.* (2013)	Time series 01/1985 – 06/ 2012 Ordinary least squares	CPI	Insignificant correlation with CPI. Gold's sensitivity to inflation was higher in the 1980s, decreased in the 1990s and increased in the 2000s.
Baur and McDermott (2016)	Time series 01/1970 – 12/ 2013 Ordinary least squares	MSCI world stock market index, S&P500, 10-year US Treasury bonds, gold, silver, the CRB commodity index, US dollar and Swiss Franc	US dollar and Swiss Franc act as safe haven. The choice for gold in times of market turmoil can be explained by investors cognitive limitations.
Baur and Lucey (2010)	Panel data 11/1995 – 11/2005 Ordinary least squares	MSCI stock and bond indices expressed in local currency	Negative correlation with stocks but not for bonds. Positive correlation with bonds.
Baur and McDermott (2010)	Panel data 03/1979 – 03/2009 OLS and GARCH	World stock indices of 13 countries	Gold is a safe haven for most developed countries. High levels of uncertainty tend to make gold co-move with stock markets.
Capie *et al.* (2005)	Time series 01/1971 – 02/2004 OLS	USD/JPY and USD/GBP exchange rates	Positive correlation with the US dollar. Gold´s sensitivity has varied over time.
Gomis-Porqueras *et al.* (2022)	Time series 06/1997 – 03/2021 PSY procedure	European sovereign debt, oil inflation, equity, the US dollar exchange rate and Covid-19 pandemic risks	Gold serves as safe haven in extreme market conditions. Gold showed weak safe haven properties during the Covid-19 pandemic.

Figure A8: Author's own elaboration

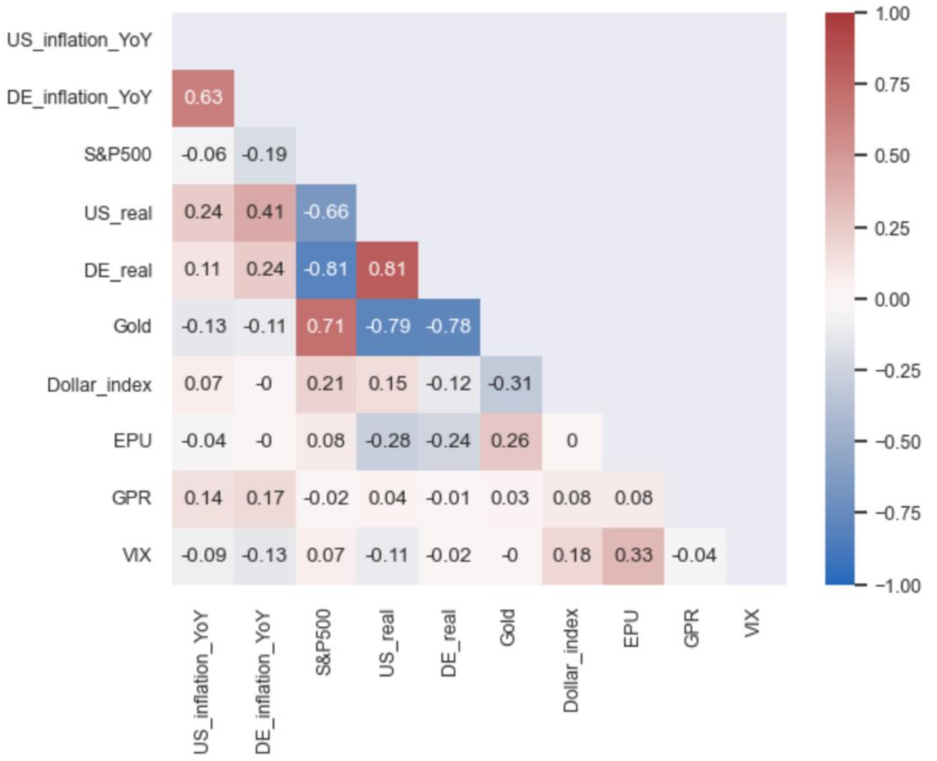

Figure A9: Correlation coefficient matrix among variables

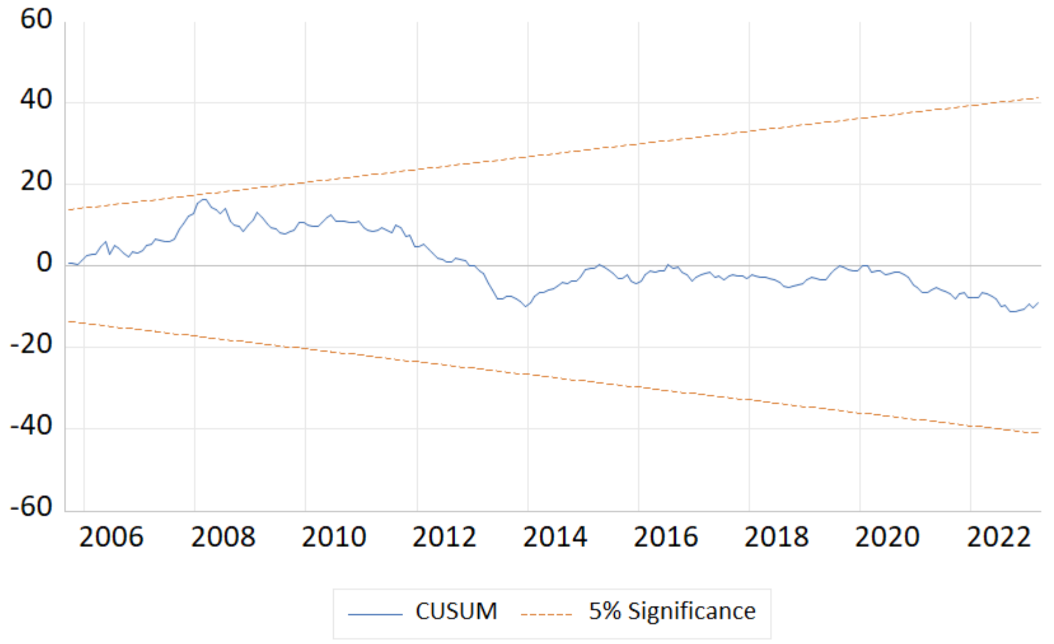

Figure A10: CUMSUM Test (at 5% significance level)

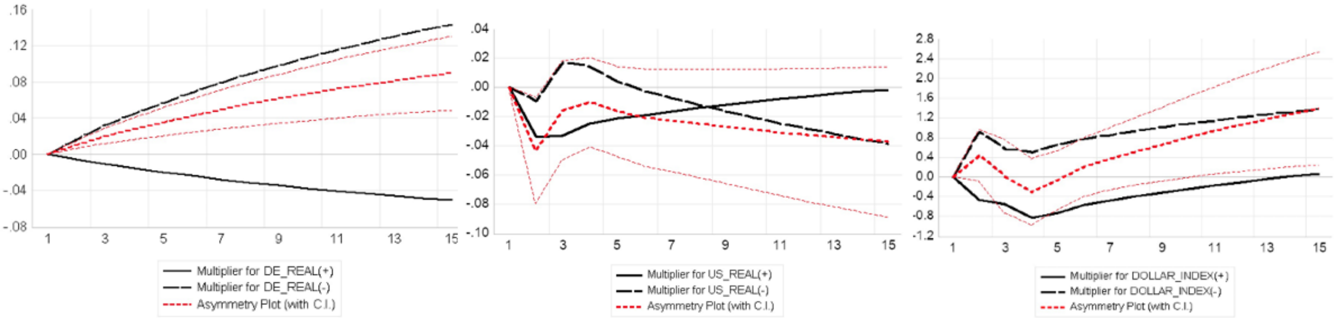

Figure A11: The cumulative dynamic multipliers for the positive and the negative changes in exogenous variables.

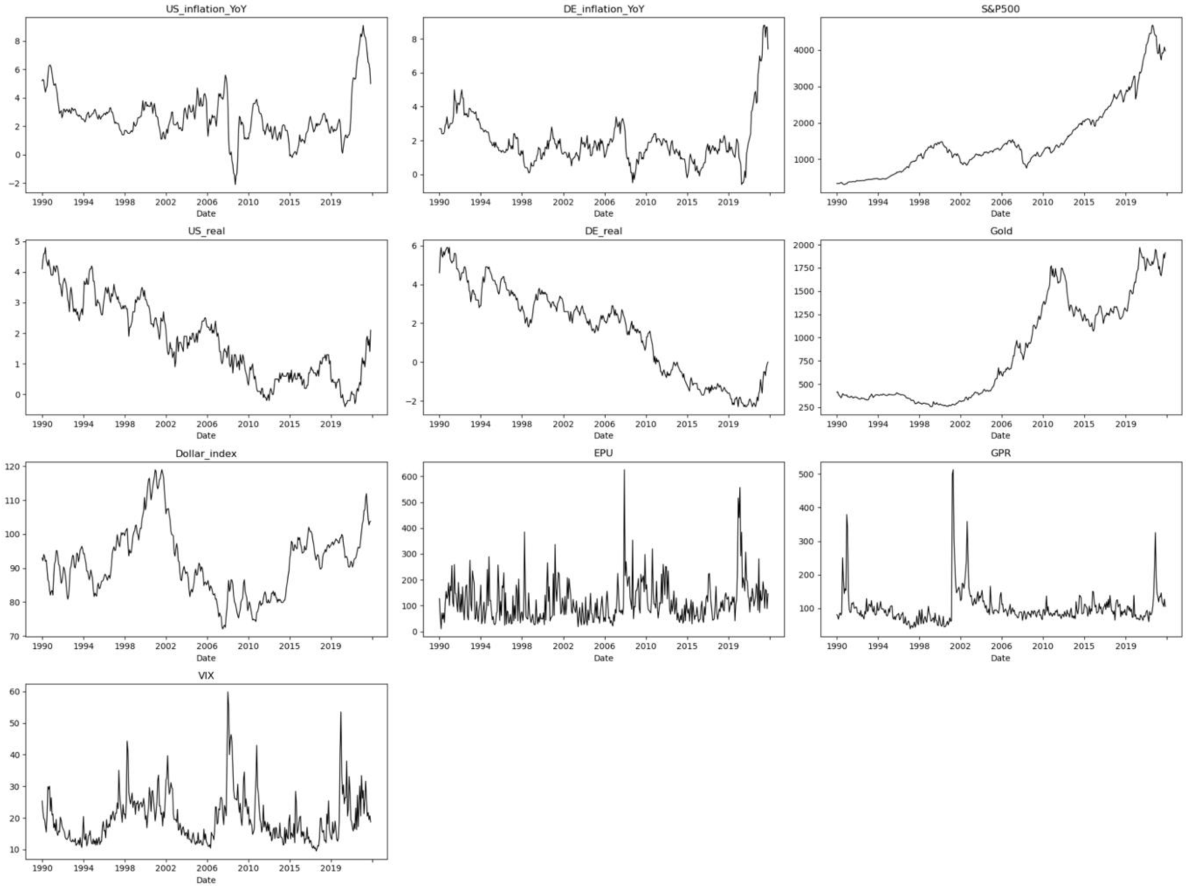

Figure A12: Graphic representation of all variables included in the econometric study, measured in levels.