Monetary effects on nominal oil prices

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ABSTRACT

The paper presents a theory of nominal asset prices for competitively owned oil. Focusing on monetary effects, with flexible oil prices the US dollar oil price should follow the aggregate US price level. But with rigid nominal oil prices, the nominal oil price jumps proportionally to nominal interest rate increases. We find evidence for structural breaks in the nominal oil price that are used to illustrate the theory of oil price jumps. The evidence also indicates strong Granger causality of the oil price by US inflation as is consistent with the theory.

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1. Introduction

An extensive literature has studied the effects of exogenous oil price shocks on macroeconomic outcomes, such as inflation, interest rates, and output (Bernanke, Gertler, & Watson, 2004; Hamilton, 1983; Kim & Loungani, 1992; Leduc & Sill, 2004). Much less has been said, however, about the factors that determine the international oil price itself.[1] While it is not impossible in principle that the *real* oil price is driven predominantly by oil sector-specific (e.g. technological) factors, largely unrelated to

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[1] A few recent exceptions include Barsky and Kilian (2001, 2004); Kilian (2009), and Nakov and Pescatori (in press-a,b).

the broader macroeconomy, it seems much more plausible that the world oil price should be affected by global macroeconomic conditions as well. The latter appears even more likely when considering the *nominal* US dollar price of oil.

In this paper we focus on changes in the nominal oil price that must occur in equilibrium just to offset persistent shifts in US inflation. We view such inflation shifts as rooted in persistent changes in the growth rate of the money supply. The oil price changes take place in a competitive setting in which it is costly to renegotiate oil contracts. The latter gives rise to a pricing condition for the nominally rigid oil price whereby the newly set nominal oil price builds in the expected future inflation.

The model is in the minimalist setting that can illustrate the theory. It is a representative agent, deterministic, cash-in-advance economy that incorporates oil as an input to the production process of the final consumption good. In Section 2 we present evidence of nominally rigid oil prices prior to the mid 1980s. When the nominal oil price is stable within inflation regimes as during this period, our model implies that, from one inflation regime to the next, the oil price must jump in line with the change in the nominal interest rate net of output growth. This adjustment is necessary to restore equilibrium so that the oil firm's owners earn a competitive return on their fixed factor of production, the oil field (Section 3). The driving forces in our setup are infrequent persistent changes in the rate of inflation rooted in exogenous money supply changes. We test for and date such breaks in inflation regimes using a test for multiple structural breaks due to Bai and Perron (1998) (Section 4). We find evidence for four such breaks in the postwar period: two upward shifts in 1967 and 1973, and two downward shifts in 1982 and 1992 (see the top panel of Fig. 2); we identify three related breaks in the nominal oil price: two upward jumps in 1973, 1979, and a crash in 1985. Using the estimated break dates, we compute the oil price changes implied by the model and contrast them with the actual oil price changes, showing that the theory is consistent with the data for the period of rigid oil prices. In addition, we revisit Hamilton's (1983) Granger causality tests. At first we replicate Hamilton's result that inflation did not Granger-cause the oil price prior to 1973. However, we find robust evidence that the oil price is Granger caused by US inflation since 1973. Qualifications and possible extensions are discussed in Sections 5 and 6, and an extension considering nominal gold prices is made in a similar fashion in Appendix A.

2. Stylized facts of nominal oil price change

Fig. 1 graphs the annual percentage change in the nominal oil price versus the annual percentage change in the *rate* of inflation (the annual *acceleration* of the price level) for the period from 1957 to 2009. Inflation is defined in the usual way as the annual percentage change in the consumer price index (with the energy component removed). The figure shows that nominal oil prices were relatively unchanging before 1985, except for big spikes around 1974 and 1979, while the inflation rate moved around throughout the period. The spikes represent movements to new oil price levels that for a while remain relatively unchanged. With the oil price stable up to the first spike, between the first two spikes, and between the second spike and around 1985, these periods may characterize different "regimes" of oil price levels. Starting around 1985, oil price changes begin following inflation rate changes rather closely.

Alternatively, looking directly at the monthly series for the US dollar West Texas Intermediate oil price (in the middle panel of Fig. 2) it is clear that, at least up until 1979, the nominal oil price was changed rather infrequently. A closer look at the data reveals that the average price spell for the period from 1957 to 1979 was more than a year (and close to a year-and-a-half if we exclude the couple of occasions with two or three consecutive price changes of a few cents); the longest price spell is around 2 years; other nominal oil price series, such as the series compiled by the IMF, show even more rigid behavior.

The above pattern has to do with the fact that prior to the 1979 Iranian revolution, much of the oil market was dominated by long-term contracts with oil companies (Biolsi, 1995). In particular, Hamilton (1983) documents the practice of "posted" oil prices during the "pre-OPEC" period, and the regulatory defense of posted prices by the Texas Railroad Commission and other US state regulatory agencies. The commissions tended to keep the nominal price of oil constant, allowing the quantity produced to fluctuate to meet demand, unless a large disturbance occurred. This policy of keeping the
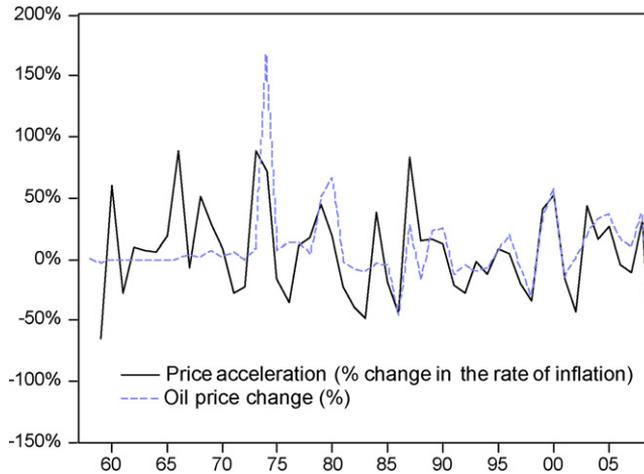
Fig. 1. Annual Price Acceleration and Oil Price Changes (%). Note: Annual price acceleration is defined as $\Delta\pi_t/\pi_{t-1}$, where $\pi_t = \Delta P_t/P_{t-1}$; t refers to a year and P_t refers to CPI less energy. Example 1: a doubling of the rate of inflation from 2% to 4% is a 100% acceleration of the price level: (4−2)/2=100%. Example 2: a fall of inflation from 3% to 1% is a −66.7% acceleration of the price level: (1−3)/3=−66.7%. In the period from 1957 to 2009 there was only one year in which the annual inflation rate was negative: 2009.

dollar price of oil fixed between major realignments was maintained in the OPEC era (Rotemberg & Woodford, 1996; Samii, 1995).

At the same time, the oil industry was conscious of the erosion of the real price of oil through inflation and was "anxious to make up for this loss at any opportunity" (Hamilton, 1983). According to LaFeber (1993) "the Arab-Israeli conflict triggered a crisis already in the making. . . The West could not continue to increase its energy use 5% annually, pay low oil prices, yet sell inflation-priced goods to the petroleum producers in the Third World".[2]

Thus, the prevalence of long term contracts and the actions of oil commissions, combined with the continuous erosion of oil profits through inflation, set the stage for the infrequent and large oil price adjustments seen in the data during this period. In the following section we lay out a simple model meant to account for the size of oil price changes, given the attendant changes in the rate of inflation.

3. The model

The model is a standard deterministic perfect foresight representative agent economy, with oil used as an intermediate input in the production of final goods. The representative agent produces the final good and consumes it. There is a representative firm, the oil producer, which rents capital and labor from the consumer. The oil firm owns a fixed input, the oil field, which is assumed to grow at the exogenous growth rate of output. The fixed input gives long term competitive rents to the oil firm. The consumer in turn owns the oil firm and gets these rents back as income.

3.1. Representative agent problem

The agent as a consumer maximizes the preference-discounted stream of period utility subject to an income and an exchange constraint. Let the utility function be denoted by $u(\cdot)$ with the aggregate

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[2] In an interview for the New York Times in 1973 the Shah of Iran, the world's second-largest exporter of oil at the time, said: "Of course [the price of oil] is going to rise,". "Certainly! . . . You [western nations] increased the price of wheat you sell us by 300%, and the same for sugar and cement. . . You buy our crude oil and sell it back to us, redefined as petrochemicals, at a hundred times the price you've paid to us. . . It's only fair that, from now on, you should pay more for oil" (LaFeber (1993), p. 292).
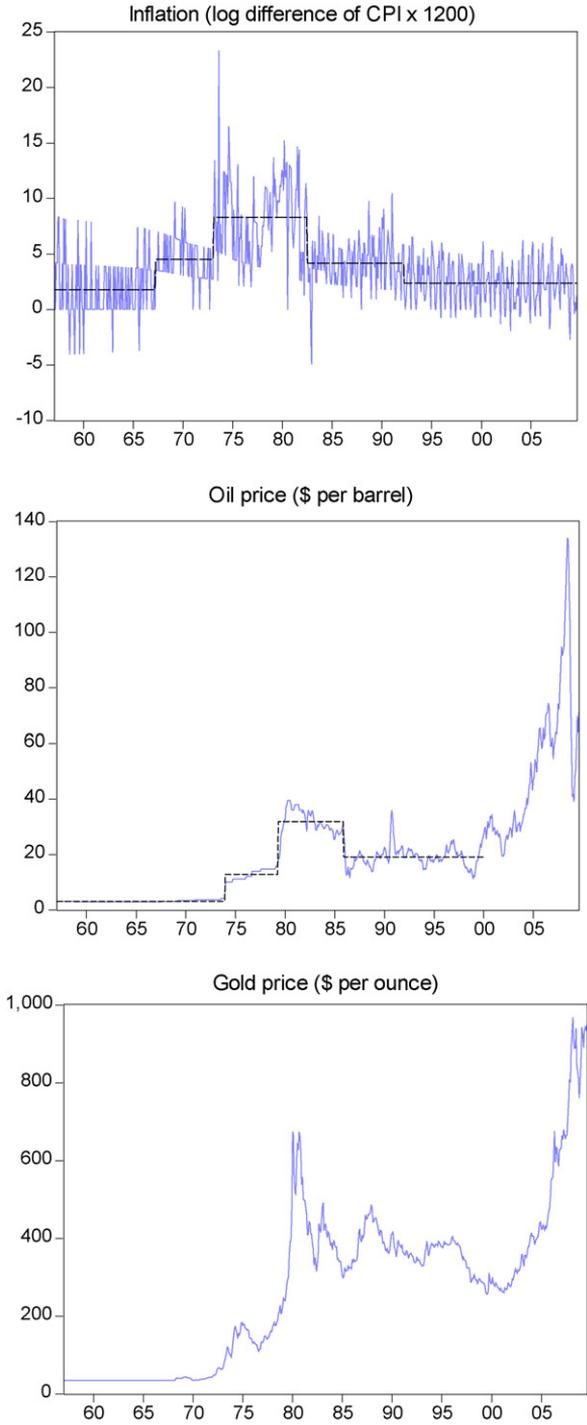
Fig. 2. Inflation, oil price, gold price.

consumption good at time t, denoted by c_t, and leisure time, denoted by x_t, entering as arguments,

$$u_t = u(c_t, x_t).$$ (1)

The output of goods production, denoted by y_t, is divided between consumption and investment. Human capital h_t augments the raw labor time in the production of goods and oil, and is assumed to grow at an exogenous rate g_t; $h_{t+1} = h_t(1 + g_{t+1})$.

The agent as a producer of goods has a production function that uses effective labor, $l_t h_t$, capital denoted by k_t, and oil as an intermediate input, denoted by i_{Ot}. Capital is used in two ways, as an input in goods production, and also as rented to the oil firm for use in oil production.

The share of capital used for goods production, s_t, and oil production, s_{Ot}, add to one,

$$s_t + s_{Ot} = 1.$$ (2)

The shares of time also add to one. With l_{Ot} being the time spent working for the oil firm, the time constraint is,

$$1 = x_t + l_t + l_{Ot}.$$ (3)

The goods production function is assumed to have constant returns to scale in the three inputs, with the following form,

$$y_t = f(s_t k_t, i_{Ot}, l_t h_t).$$ (4)

With investment in capital denoted by i_t and the depreciation rate by δ, the capital accumulation equation is given by,

$$i_t = k_{t+1} - k_t(1 - \delta)$$ (5)

The consumer works for the goods producer and the oil firm, offering labor for wages $w_t(l_t + l_{Ot})h_t$ and capital for rents $r_t k_t$.

The agent faces a constraint that consumption goods are bought with cash, giving rise to the standard (Clower, 1967) condition. With the nominal price of the aggregate consumption good denoted by P_t, and the money stock denoted by M_t, this exchange constraint is,

$$M_t = P_t c_t.$$ (6)

Let z_{Ot} denote the number of shares in the oil firm held at time t, V_{Ot} the price of a share, D_{Ot} the per-share dividend, and R_t the net nominal interest rate. Let the nominal price of oil be denoted by P_{Ot}. The agent's nominal income constraint sets the nominal value of goods output $P_t f$, plus the nominal income from labor $P_t w_t l_{Ot} h_t$ and capital $P_t r_t s_{Ot} k_t$ employed in oil production, plus the total dividends of the oil firm $D_{Ot} z_{Ot}$, and plus a cash transfer H_t, to outlays on consumption $P_t c_t$, investment in capital $P_t i_t$, and in oil $P_{Ot} i_{Ot}$, in money $M_{t+1} - M_t$, and in bond holdings $B_{t+1} - (1 + R_t)B_t$, and investment in oil firm stocks $V_{Ot}(z_{Ot+1} - z_{Ot})$. Substituting in the capital and time allocation constraints in Eqs. (2) and (3), the nominal income constraint becomes,

$$P_t f\left[(1 - s_{Ot})k_t, i_{Ot}, (1 - x_t - l_{Ot})h_t\right] + P_t w_t l_{Ot} h_t + P_t r_t s_{Ot} k_t + D_{Ot} z_{Ot} + H_t$$
$$= P_t c_t + P_t \left[k_{t+1} - k_t\left(1 - \delta\right)\right] + M_{t+1} - M_t + B_{t+1} - (1 + R_t)B_t + V_{Ot}(z_{Ot+1} - z_{Ot}) + P_{Ot} i_{Ot}.$$ (7)

3.2. Government

The nominal money stock, denoted by M_t, is exogenously supplied through lump sum transfers to the consumer. With H_t denoting the lump sum transfer, the supply equation is

$$M_{t+1} = M_t + H_t.$$ (8)

We further denote the money supply growth rate by $\bar{\sigma}_t$, where $H_t = \bar{\sigma}_t M_t$. We assume that $\bar{\sigma}_t$ is constant, except for infrequent exogenous shifts marking breaks in inflation regime, which we test for and date in Section 4.

3.3. Oil firm

Oil is produced with a CRS function using labor $l_{Ot}h_t$, capital $s_{Ot}k_t$, and an exogenous endowment input, F_t, denoting oil fields,

$$i_{Ot} = (l_{Ot}h_t)^{\gamma_1}(s_{Ot}k_t)^{\gamma_2}F_t^{1-\gamma_1-\gamma_2}. \tag{9}$$

The oil fields are assumed to grow over time at the exogenous growth rate g_t, so that $F_{t+1} = F_t(1 + g_{t+1})$. The competitive oil firm earns a positive profit because of the scarcity of this fixed input. The oil output i_{Ot} is sold to the goods producer for the nominal value of $P_{Ot}i_{Ot}$. The current period nominal profit of the oil firm is paid out as the dividend D_{Ot} to the shareholders,

$$D_{Ot} = P_{Ot}(l_{Ot}h_t)^{\gamma_1}(s_{Ot}k_t)^{\gamma_2}F_t^{1-\gamma_1-\gamma_2} - P_t w_t l_{Ot}h_t - P_t r_t s_{Ot}k_t. \tag{10}$$

The oil firm maximizes the present discounted stream of profits at time t, equal to the current dividend D_{Ot} plus the share price V_{Ot}. The share price in turn equals the stream of expected future dividends, discounted by the nominal rate of interest,

$$V_{Ot} = \sum_{s=t+1}^{\infty}\left[\frac{D_{Os}}{\prod\limits_{j=t+1}^{s}\left(1+R_j\right)}\right]. \tag{11}$$

The oil firm thus maximizes,

$$\max_{\{s_{Ot}, l_{Ot}\}_{t=0}^{\infty}} \sum_{s=t}^{\infty}\left[\frac{D_{Os}}{\prod\limits_{j=t}^{s}\left(1+R_j\right)}\right], \tag{12}$$

subject to (10), where the summation starts from period t.

The first-order conditions for this maximization are that, for all t, the marginal products equal the factor prices,

$$\gamma_1\left(\frac{P_{Ot}}{P_t}\right)\left(\frac{i_{Ot}}{l_{Ot}h_t}\right) = w_t; \tag{13}$$

$$\gamma_2\left(\frac{P_{Ot}}{P_t}\right)\left(\frac{i_{Ot}}{s_{Ot}k_t}\right) = r_t. \tag{14}$$

Substituting from Eqs. (13) and (14) for the factor prices, into the dividend Eq. (10), yields

$$D_{Ot} = \gamma P_{Ot}i_{Ot}, \tag{15}$$

where $\gamma \equiv 1 - \gamma_1 - \gamma_2$ is the income share of the oil field. Then, the maximized present discounted value of current and future profits is given by,

$$D_{Ot} + V_{Ot} = \sum_{s=t}^{\infty}\left[\frac{\gamma P_{Os}i_{Os}}{\prod\limits_{j=t}^{s}\left(1+R_j\right)}\right]. \tag{16}$$

3.4. Equilibrium

The consumer maximizes utility subject to constraints, taking the prices of goods, factors of production (including oil), bonds, as well as the money transfer, as given. The oil firm similarly takes goods, factor, bond, and oil prices as given. The consumer maximizes the present discounted sum of utility (1), with respect to c_t, x_t, s_{Ot}, l_{Ot}, k_{t+1}, i_{Ot}, M_{t+1}, B_{t+1}, and z_{Ot+1}, given that $\beta \in (0, 1)$, and subject to constraints (6) and (7). Defining the relative price of oil as $p_{Ot} \equiv P_{Ot}/P_t$, and the inflation rate as $\pi_t = P_{t+1}/P_t - 1$, the first-order conditions can be written as:

$$\frac{u_1(c_t, x_t)}{u_2(c_t, x_t)} = \frac{1 + R_t}{w_t h_t}, \tag{17}$$

$$1 + g_t = \beta\left(1 + r_t - \delta\right), \tag{18}$$

$$f_1(s_t k_t, i_{Ot}, l_t h_t) = r_t, \tag{19}$$

$$f_2(s_t k_t, i_{Ot}, l_t h_t) = p_{Ot}, \tag{20}$$

$$f_3(s_t k_t, i_{Ot}, l_t h_t) = w_t, \tag{21}$$

$$\frac{V_{Ot+1} + D_{Ot+1}}{V_{Ot}} = 1 + R_{t+1}, \tag{22}$$

$$1 + R_t = \left(1 + r_t - \delta\right)(1 + \pi_t), \tag{23}$$

$$1 + R_t = (1 + \bar{\sigma}_t)/\beta. \tag{24}$$

Going by each condition respectively, in (17) the marginal rate of substitution between goods and leisure equals the ratio of the shadow goods cost, including R_t as the exchange cost, to the effective real wage. Assuming $u_1(c_t, x_t) = 1/c_t$ for consistency with balanced growth, by (18) the exogenous growth rate of output equals the marginal product of capital net of depreciation multiplied by the time discount factor. From (19), (20), and (21), the capital, oil, and labor factor prices are equal to the inputs' marginal products in goods production. Eq. (22) in turn gives the nominal asset pricing condition for the oil firm's share price, with the nominal return on investing in the oil firm equal to the nominal rate of interest. Condition (23) is the Fisher equation for the nominal interest rate as the sum of the real interest rate and inflation. And finally, Eq. (24) shows the dependence of the nominal interest rate on the exogenous growth rate of the money supply.

Note that writing the asset pricing Eq. (22) in real terms by dividing by the price of goods P_t, and using the Fisher Eq. (23), the real return to investing in the oil firm is equal to the real rate of return on capital,

$$\frac{(V_{Ot+1}/P_{t+1}) + (D_{Ot+1}/P_{t+1})}{V_{Ot}/P_t} = 1 + r_{t+1} - \delta. \tag{25}$$

3.4.1. Competitive equilibrium balanced growth path

The definition of the balanced growth path equilibrium for the consumer requires that c_t, k_t, i_t, i_{Ot}, M_t/P_t, V_{Ot}/P_t, and D_{Ot}/P_t all grow at the same constant growth rate g, while leisure x_t and the capital and labor shares s_t, s_{Ot}, l_t, and l_{Ot}, are stable; shares in the oil firm z_t are unity in equilibrium, as the consumer owns 100% of the oil firm.

Proposition 1. *Along the balanced-growth path, the real value of the oil firm's stock is equal to the present discounted stream of the real returns to the fixed factor (the oil field),*

$$\frac{D_{Ot} + V_{Ot}}{P_t} = \gamma p_{Ot} i_{Ot} \left(\frac{1 + r_t - \delta}{r_t - g_t}\right), \quad and \quad \frac{V_{Ot}}{P_t} = \gamma p_{Ot} i_{Ot} \left(\frac{1 + g_t - \delta}{r_t - g_t}\right).$$

Proof. The present discounted value of Eq. (16) can be written in real terms by dividing by the nominal goods price,

$$\frac{D_{Ot} + V_{Ot}}{P_t} = \gamma \left(\frac{P_{Ot}}{P_t} \right) i_{Ot} + \frac{(\gamma P_{Ot+1}/P_{t+1})(P_{t+1}/P_t)i_{Ot+1}}{1 + R_{t+1}}$$

$$+ \frac{(\gamma P_{Ot+2}/P_{t+2})(P_{t+2}/P_{t+1})(P_{t+1}/P_t)i_{Ot+2}}{(1 + R_{t+1})(1 + R_{t+2})} + \cdots$$

Using the Fisher equation of interest rates (23), this reduces to

$$\frac{D_{Ot} + V_t}{P_t} = \gamma \frac{P_{Ot}}{P_t} i_{Ot} + \frac{\gamma (P_{Ot+1}/P_{t+1})i_{Ot+1}}{1 + r_{t+1} - \delta} + \frac{\gamma (P_{Ot+2}/P_{t+2})i_{Ot+2}}{\left(1 + r_{t+1} - \delta\right)\left(1 + r_{t+2} - \delta\right)} + \cdots \tag{26}$$

Along the balanced growth path, human and physical capital stocks h_t and k_t, and oil i_{Ot}, grow at the same constant rate g, while s_{Ot} and l_{Ot} are constant. Thus, the input ratios $i_{Ot}/(l_{Ot}h_t)$ and $i_{Ot}/(s_{Ot}k_t)$ are constant; since the real factor prices r_t and w_t are also constant (from Eqs. (19) and (21)), the real oil price $p_{Ot} \equiv P_{Ot}/P_t$ in Eqs. (13) and (14) must also be constant. So the nominal oil price P_{Ot} must move one-to-one with the aggregate price level for any given money supply growth rate. Since r_t is constant, this implies that along the balanced growth path Eq. (26) reduces to the following function of real variables only,

$$\begin{aligned}
\frac{D_{Ot} + V_{Ot}}{P_t} &= \gamma p_{Ot} i_{Ot} + \frac{\gamma p_{Ot} i_{Ot} (1 + g_t)}{1 + r_t - \delta} + \frac{\gamma p_{Ot} i_{Ot}(1 + g_t)^2}{\left(1 + r_t - \delta\right)^2} + \cdots \\
&= \gamma p_{Ot} i_{Ot} \left(\frac{1 + r_t - \delta}{r_t - \delta - g_t} \right).
\end{aligned} \tag{27}$$

In turn,

$$\frac{V_{Ot}}{P_t} = \frac{D_{Ot} + V_{Ot}}{P_t} - \frac{D_{Ot}}{P_t} = \gamma p_{Ot} i_{Ot} \left(\frac{1 + g_t}{r_t - \delta - g_t} \right). \tag{28}$$

where on the right hand side of the first equality we have used (15) expressed in real terms. □

3.4.2. Rigid oil price contracts with growing oil supply

Abstracting from the vast contracting literature, and guided by the intuition of Gray (1978), it is assumed that oil supply contracts are costly to change. We assume that all contracts determine the quantity and the nominal oil price, as agreed upon between the consumer buying the oil for use in production and the oil firm producing and selling the oil. In particular, the nominal price P_{Ot} is fixed for all future time, and the supply of oil is fixed at i_{Ot} with a set growth rate of g_t. As an additional clause of the contract, it is assumed that the nominally fixed oil price can change only if the exogenous money supply growth rate has changed in a persistent fashion; then, the oil price is reset to a new level consistent with the new competitive balanced growth path conditions.[3]

Suppose the oil contract has just been renegotiated. With the fixed nominal oil price at time t denoted by $\bar{P}_{Ot}$, the current value of the oil firm's optimal profit stream, from Eq. (11), is now given by

$$V_{Ot} = \sum_{s=t+1}^{\infty} \left[\frac{\gamma \bar{P}_{Os} i_{Os}}{\prod\limits_{j=t+1}^{s} \left(1 + R_j\right)} \right]. \tag{29}$$

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[3] In a more standard (s, S)-type model of infrequent oil price changes, the *timing* of oil price changes would be an endogenous variable as well, with oil price changes occurring whenever the gain from adjusting exceeds a given fixed cost of adjustment. We abstract from the complications arising from such a dynamic stochastic setup, focusing instead only on the intensive margin of adjustment in steady state, that is, on the *size* of the oil price changes necessary to restore balanced growth path, competitive, equilibrium.

Proposition 2. *With fixed nominal oil price contracts, the nominal asset pricing condition implies that, for a small cost of recontracting, the required percentage change of the nominal oil price is approximately equal to the percentage change of the nominal interest rate net of the growth rate,*

$$\frac{\bar{P}_{Ot+1}}{\bar{P}_{Ot}} \simeq \left(\frac{R_{t+1} - g_{t+1}}{R_t - g_t} \right).$$

Proof. Writing out the terms in (29) and using the balanced growth path conditions (including the fact that, within any given inflation regime, the nominal interest rate remains constant), the above expression becomes,

$$
\begin{aligned}
V_{Ot} &= \frac{\gamma \bar{P}_{Ot} i_{Ot+1}}{1 + R_{t+1}} + \frac{\gamma \bar{P}_{Ot} i_{Ot+2}}{(1 + R_{t+1})(1 + R_{t+2})} + \cdots \\
&= \frac{\gamma \bar{P}_{Ot} i_{Ot} (1 + g_t)}{1 + R_t} + \frac{\gamma \bar{P}_{Ot} i_{Ot} (1 + g_t)^2}{(1 + R_t)^2} + \cdots \\
&= \gamma \bar{P}_{Ot} i_{Ot} \left(\frac{1 + g_t}{R_t - g_t} \right).
\end{aligned}
\tag{30}
$$

Adding the current period nominal dividend, $\gamma \bar{P}_{Ot} i_{Ot}$, yields

$$D_{Ot} + V_{Ot} = \gamma \bar{P}_{Ot} i_{Ot} \left(\frac{1 + R_t}{R_t - g_t} \right). \tag{31}$$

Forwarding Eq. (31) by one period and substituting the resulting equation together with (30) into the no-arbitrage condition (22), we obtain

$$\frac{V_{Ot+1} + D_{Ot+1}}{V_{Ot}} = \frac{\gamma \bar{P}_{Ot+1} i_{Ot+1}(1 + R_{t+1})/(R_{t+1} - g_{t+1})}{\gamma \bar{P}_{Ot} i_{Ot}(1 + g_t)/(R_t - g_t)} = 1 + R_{t+1}. \tag{32}$$

It follows that, along the balanced growth path with $i_{Ot+1} = (1 + g)i_{Ot}$, and assuming a small recontracting cost,

$$\frac{\bar{P}_{Ot+1}}{\bar{P}_{Ot}} \simeq \frac{R_{t+1} - g_{t+1}}{R_t - g_t}. \quad \square \tag{33}$$

The Proposition shows that the nominal asset pricing equation for the oil firm's stock is respected if the price of oil jumps in proportion to the increase in the nominal interest rate net of the growth rate. A similar condition is derived for the price of gold in Appendix A.

Although this relationship between oil prices and the nominal interest rate must hold eventually for changes from one balanced growth path to the next, we grant that is says nothing about the specific path of transition from one steady-state to the next, or account for any possible delays in the transmission from inflation to the oil price. Yet, the formula is suggestive of what would happen eventually should there be an exogenous change in the growth rate of the money supply. Imagine that money supply growth increases at time $t + 1$, from $\bar{\sigma}_t$ to $\bar{\sigma}_{t+1}$, and that it is expected to stay at that level for all time into the future. By Eq. (24), R_{t+1} increases relative to R_t. Then, Eq. (33) gives the new equilibrium oil price $\bar{P}_{Ot+1}$ consistent with the oil firm earning a competitive return on its fixed input, and the economy operating along the new equilibrium balanced growth path.

Propositions 1 and 2 suggest that in either case – rigid oil price contracts or inflation-indexed contracts – the oil price will react to inflation shocks. Combining Eqs. (24), (23), and (18), inflation in turn is directly affected by the exogenous money supply changes, $1 + \bar{\sigma}_t = (1 + g_t)(1 + \pi_t)$.

In the following section we compute the oil price changes implied by Eq. (33) and compare them to the actual oil price realignments from one regime to another found in the data. In addition, we revisit Hamilton's Granger-causality evidence regarding the non-causality of the oil price by US inflation.

4. Inflation breaks and oil price changes: a numerical illustration

In this section we offer a simple illustration of the ability of our model to explain oil price changes as rooted in inflation regime shifts. We first test for and date changes in inflation regimes using a popular statistical test for multiple structural breaks due to Bai and Perron (1998). Using the same technique we then identify subsequent shifts in the nominal oil price. Given the oil price break dates, we apply the oil pricing formula derived from our theoretical model to the data, comparing actual with predicted oil price changes. We show that our simple model is capable of explaining a substantial fraction of the observed oil price shifts. Finally, we revisit the Granger-causality evidence reported by Hamilton (1983), checking the robustness of his results with respect to the data period and to the presence of structural breaks.

The data sample includes 632 monthly observations from January 1957 to August 2009 of the US consumer price index (for all items less energy), the 10-year Treasury bill rate, the dollar prices of oil and gold, and quarterly data on the real US GDP. All variables except the price of gold are taken from the St. Louis Fed's FRED II database; the gold price is available from the International Financial Statistics compiled by the IMF. The latter is included as part of an extension of the theory to gold prices as outlined in Appendix A. Table 1 defines the variables used.

4.1. Testing for and dating structural breaks

We identify inflation regime changes with breaks in the intercept of the inflation equation of a bivariate VAR including the log difference of CPI and the nominal price of oil. We apply the Bai and Perron (1998) sequential test for structural breaks, allowing for up to five breaks in the intercept. Formally, the test is based on the following regression equation,

$$\Delta \log(P_t) = \alpha_0 + \sum_{i=1}^{m} \alpha_i D_{i,t} + \sum_{i=1}^{k} \beta_i \Delta \log(P_{t-i}) + \sum_{i=1}^{k} \gamma_i P_{O,t-i},$$

where $D_{i,t} = 1(t > T_i)$ are dummy variables with T_i denoting the timing of the ith break, and m is the maximum allowed number of breaks (five in our case). The Bai and Perron (1998) test first searches for a single break, the timing of which is determined endogenously; once a break is found, the sample is split at the estimated break date and each subsample is tested again for a break; this process continues until the test fails to find any additional breaks, or until the maximum allowed number of breaks is reached. Table 2 reports the estimated break dates, the statistical significance level at which they are found, as well as a 90% confidence interval for each break.

We find four breaks in the inflation equation: two upward shifts in 1967 and 1973, and two downward shifts in 1982 and 1992. These breaks can be seen in Fig. 2, which shows that average inflation more than doubled from 1.8% per year during 1957–1967 to 4.5% during 1967–1973, and then almost doubled again to 8.3% during 1973–1982. In contrast, moving to 1982–1992 the mean of inflation was halved to 4.1%, and then it was almost halved again to 2.4% from 1992 on.

Our theory cannot account for the recent run-up and collapse of oil prices since Y2K as rooted in inflation changes. Hence, when analyzing the oil price, we work with a subsample from January 1957 to December 1999. For this subsample, and using the same procedure as before, we identify three breaks in the mean oil price: two upward shifts in 1974 and 1979, and a crash in 1985. These are clearly seen in Fig. 1, and the statistical procedure dates them even more precisely than the inflation breaks.

Table 1
Data series.

P	US consumer prices, all items less energy (seas. adj.), 1982–1984 = 100
g	4× log difference of quarterly real GDP (billions of 2005 dollars, seas. adj.)
R	monthly yield on 10-year Treasury bills (%)
P_O	West Texas intermediate oil price, $ per barrel
P_G	price of gold, London, $ per ounce

Table 2
Estimated break dates.

Break dates	Significance	90% Confidence interval
Inflation		
Apr. 1967	5%	−8/+6 months
Feb. 1973	10%	−13/+3 months
Jul. 1982	5%	−8/+23 months
Apr. 1992	5%	−16/+21 months
Oil price		
Jan. 1974	2.5%	−4/+0 months
May 1979	2.5%	−2/+1 months
Dec. 1985	2.5%	−6/+4 months

Note: Max. five breaks allowed; the trimming parameter for the sup$F(l+1|l)$ test is 0.1.

Table 3
Nominal interest rates, GDP growth rates, oil and gold prices.

Regime	10-Year rate (1)	Growth rate (2)	Oil price		Gold price		Model %Δ (7)
			Average (3)	%Δ (4)	Average (5)	%Δ (6)	
1.1957–1974	4.98	3.85	3.15		41.00		
2.1974–1979	7.88	2.97	12.85	4.08	162.29	3.96	4.35
3.1979–1985	11.87	2.71	31.94	2.49	416.78	2.57	1.87
4.1985–1999	7.16	3.28	19.10	0.60	366.99	0.88	0.42
5.1999–2009	4.49	1.66	50.31	2.63	503.29	1.37	0.73

The first jump in the price of oil is clearly preceded by the first upward shift in inflation in 1967. Moreover, the 90% confidence interval for the second upward shift in inflation in 1973 precedes the confidence interval for the 1974 oil price jump, implying that the second persistent increase in inflation, too, started *before* the first "oil price shock". Likewise, the oil price "crash" of 1985 was preceded by the sharp disinflation initiated in 1982. Precedence does not prove causality, but these episodes are at least consistent with the hypothesis that changes in the inflation regime may be responsible for permanent shifts in the nominal oil price as suggested by our model.

Although we were not able to identify statistically specific break dates for the gold price, comparing panels 2 and 3 of Fig. 2, concurrent movements in the gold price show a striking similarity to those of the oil price. Therefore, we include the gold price in the model computation below to show that it also appears to be reflecting inflation changes; however, the lack of discrete level breaks suggests that gold had a much more flexible price throughout the period. Indeed, the two dramatic increases in the period 1970–1975 and 1978–1980, and the subsequent decrease from 1981 to 1985, were more gradual, although of similar proportion to the abrupt shifts in the oil price.

4.2. Oil price changes implied by the model

To illustrate simply the implications of the model of rigid oil prices, here we use the estimated structural breaks to compare the model's implied changes in the price of oil (and gold) to the actual changes. Since the breaks for the oil price are the most clearly demarcated, they will be used to define the regime periods.[4]

We thus consider that the change in the rigid oil price in itself is the characterization of the structural break, as in the middle panel of Fig. 2; this gives four regimes: from 1.1957 to 12.1973, 1.1974 to 4.1979, 5.1979 to 11.1985, and 12.1985 to 12.1999. Table 3 presents the average long term US nominal interest rate (%), the average GDP growth rate (%), and the changes, from one regime to the next, in the average prices of oil and gold observed in the data.

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[4] Finding common structural changes across a system of multivariate equations is still in its early stages of development; see Qu and Perron (2007) for an advance on this.

Using the formula in Eq. (33), applied to the above regime intervals for oil prices, we obtain the final column of Table 3. Compare this with the actual price changes in columns 4 and 6. For the first oil price change, from Regime 1 to 2, the computation is 4.35, while the actual oil price change is 4.08. For the next two changes, from 2 to 3 and from 3 to 4, the computation is somewhat below the actual oil price changes (1.9 versus 2.5, and 0.4 versus 0.6). For the last regime change, from 4 to 5, the model predicts an oil price decline, while the actual oil price increased substantially.

As discussed in Section 2, in the first two subperiods up to 1979 most oil trade was carried out by long-term contracts, making the nominal oil price relatively stable. This can explain the ability of the model to be close to the actual oil price changes in the first two rows of Table 3. The ability of the model to also be close to the change in the oil price in the third row, of 0.6 compared to the model's 0.4, suggests the interpretation, from the point of view of the model, that the oil price drop in 1985 was also largely (dis)inflation-related. As a summary measure, consider, for the first three regime changes, multiplying together the actual oil price changes:

$$\frac{\bar{P}_{O2}}{\bar{P}_{O1}} \frac{\bar{P}_{O3}}{\bar{P}_{O2}} \frac{\bar{P}_{O4}}{\bar{P}_{O3}} = (4.08)(2.49)(0.60) = 6.07,$$

a 607% increase. In comparison, the model's computation gives

$$(4.35)(1.87)(0.42) = 3.44,$$

a 344% increase. So it could be interpreted that the model accounts for 344/607, or 57%, of the total oil price change.

The oil price change occurring in moving to the last regime, from 1999 to 2009, however, is much larger than the model computation predicts, suggesting that this later price change was not just inflation adjustment, but also a substantial increase in the relative price of oil. This is consistent with the view of real commodity price increases due to growing demand from Asian economies, such as China.[5]

Gold price changes are roughly similar in proportion to the oil price shifts, and so the model's computations compare almost as well for gold prices too.

4.3. Granger causality evidence

Finally, we perform Granger (1969)-causality tests to determine whether past inflation can improve significantly on the prediction of the price of oil based on its own lagged values alone. We base the tests on bivariate VARs (with twelve and with twenty four lags) including the log differenced nominal price of oil and first log differenced CPI. We test the robustness of the results with respect to the sample period, and to controlling for the breaks identified in the previous section. In addition, we test for reverse causality: from the price of oil to inflation. Table 4 reports the results.

In a first step we replicate Hamilton's (1983) finding, namely the lack of statistically significant evidence that inflation Granger caused the nominal price of oil prior to 1973. In particular, Hamilton failed to reject the hypothesis of "no Granger causality" from inflation to the nominal price of oil, at 10% statistical significance for his VAR with 4 quarterly lags, and at 16% for his VAR with 8 quarterly lags. Even though we use a different definition of inflation (Hamilton used the implicit price deflator for business income), a slightly different oil price series, and work with monthly rather than quarterly data, our result for the period up to 1973 is essentially the same: we do not find evidence of Granger causality from inflation to the price of oil at 13% significance for our VAR with twelve lags ($k=12$), and at 25% significance for our VAR ($k=24$) (see the first two rows of Table 4).

We then apply the same test on the more recent sample from 1973:1 to 2009:8. In rows 3 and 4 we report strong evidence that over this later period US inflation Granger-caused the nominal price of oil. Specifically, we reject Granger non-causality at 1% both in the VAR(12) and the VAR(24) specifications. This is in contrast with Hamilton's failure to find a macro series that Granger-causes oil prices prior to 1973.

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[5] June 1997 marks the date that Hong Kong was turned back over to China from the UK with this possibly marking the opening up of the Chinese economy.

Table 4
Granger causality tests.

Null hypothesis	Period	Breaks	Lags k	Obs.	F-stat	Prob.
$\Delta \log(P) \nrightarrow \Delta \log(P_O)$	57:1–72:12	No	12	179	1.4847	0.1352
		No	24	167	1.2003	0.2561
	73:1–09:8	No	12	440	2.3916	0.0054
		No	24	440	1.8782	0.0080
		Yes	12	440	2.2793	0.0083
		Yes	24	440	1.8122	0.0117
	57:1–09:8	No	12	619	2.2752	0.0079
		No	24	607	1.8816	0.0071
		Yes	12	619	2.0855	0.0162
		Yes	24	607	1.7906	0.0122
$\Delta \log(P_O) \nrightarrow \Delta \log(P)$	57:1–72:12	No	12	179	0.6469	0.7993
		No	24	167	0.5989	0.9267
		Yes	12	179	0.6744	0.7740
		Yes	24	167	0.7357	0.8056
	73:1–09:8	No	12	440	1.4062	0.1597
		No	24	440	1.4369	0.0853
		Yes	12	440	1.7336	0.0575
		Yes	24	440	1.4614	0.0759
	57:1–09:8	No	12	619	1.4759	0.1284
		No	24	607	1.3516	0.1234
		Yes	12	619	1.7583	0.0518
		Yes	24	607	1.3596	0.1190

Note: The tests "with breaks" include indicator variables for the breaks reported in Table 2 in the periods in which they apply. These are the three breaks found for the oil price in 1974, 1979 and 1985; and the four breaks found for inflation in 1967, 1973, 1982, and 1992.

We test the robustness of this finding to the presence of the three breaks in the oil price series since 1973. Rows 5 and 6 of Table 4 show that, while the inclusion of level shift dummies slightly reduces the residual predictive power of inflation for oil price changes, the tests still show strong evidence of Granger causality from inflation to the price of oil, at 1% significance for the VAR(12), and at 2% significance for the VAR(24). The results were very similar if we cut off the sample in 1999:9 instead.

For completeness, we repeat the Granger causality tests for the entire period from 1957:1 to 2009:8, with 12 and 24 lags, with and without breaks. The results, reported in rows 7–10 of Table 4 are very similar to those for the second sample. Namely, we find very strong evidence (at 1% or 2% significance) that US CPI inflation Granger-causes changes in the nominal price of oil, as predicted by the theory.

On the other hand, evidence that over the same period fluctuations in the price of oil Granger-caused US inflation is weaker. In particular, we find no evidence (80% significance) of causality from the oil price to inflation in the first period up to 1973, and somewhat stronger, but still relatively weak evidence (10–15% significance) for the second part of the sample, and for the entire period (12% significance) when structural breaks are ignored. Interestingly, when allowing for structural breaks, the evidence for causality from the oil price to inflation becomes stronger (at 6% for the VAR(12)), suggesting that oil price shocks might explain some of the cyclical inflation fluctuations *around regime-wise means* (rather than the, arguably more important, *changes in inflation regime*).

5. Discussion

The assumptions of the model, in terms of stationary balanced growth path conditions holding on into the future after any given money supply growth rate change, are a type of comparative statics exercise. We are aware that applying this exercise to a dynamic explanation of oil prices, with each regime exhibiting the stationary conditions, is counterfactual. Yet, we find it surprising that such a simple computation of oil price changes is not wildly far off from the actual changes. This illustrates some power of the theory, even if it provides no way of determining empirically that the theory is valid, or that the predicted oil prices changes fall within some acceptable confidence bounds. Therefore, the results should be viewed as a tentative illustration of the nominal phenomenon that could be behind

nominal oil price movements, abstracting from any other dynamic supply and demand factors, for the case in which the nominal oil price is rigid within inflation regimes.

Thus, the computations in the previous section support the notion of inflation catch-up and anticipation by the oil price right up until the last regime change. A contradiction of the theory is found for the last switch from regime 4 to 5, when the model's computation is of a different order of magnitude as the actual oil price change. This suggests that in this last period, after the opening up of world markets to include much broader Asian demand for commodities, an important part of the oil price change may have been related to real as opposed to nominal factors.

6. Conclusion

The deterministic analysis, with the comparative statics of a change in the money supply growth rate leading to a new regime of fixed oil prices, is an approximation to a more fully specified dynamic economy with uncertainty. Price distortions from rigid oil prices are not analyzed, and growth is assumed to be exogenous. Further steps could include making growth endogenous and determining how the distortion of rigid prices affects allocation margins. Adding in uncertain money supply shocks, and goods productivity shocks, would allow for identification of the model's properties over the business cycle, which could be compared to volatility data on oil prices. A variance decomposition of oil prices could show the relative contributions of the different shocks to the oil price volatility.

Extension of the model to include endogenous growth could look at effects of oil price changes on the balanced-path growth rate (Gillman & Kejak, 2005) and over the business cycle (Benk, Gillman, & Kejak, 2008). This might be a useful way to consider how oil price changes affect output and its growth rate (Rebelo, 2005).

Related applications of such a monetary theory of nominal asset prices could include other nominal prices that tend to remain rigid. One prominent candidate could be the fixed implicit rental price built into the price of a house. Using this natural rigidity of pre-built-in rental rates might allow the theory to explain the shooting up of house prices during the 1970s, and their subsequent fall in the early 1980s, that was tandem to the concurrent historic rise and fall of inflation.

Appendix A. Extension with gold

Consider an extension of the model to include gold, and the nominal price of gold. Gold is modeled with the assumption that it serves a reserve function for the fiat money stock; without such a reserve it is assumed that people would be unwilling to hold the fiat money. Similar to the oil production, there is a fixed input, being the gold mine F_{Gt}, which yields a competitive profit to the gold firm owner.

It is assumed that the consumer, acting as owner of the central bank, is required to hold a fraction, denoted by $\alpha \in (0, 1)$, of the nominal money stock in terms of nominal gold capital; in return the consumer receives the transfer H_t. This adds a second type of exchange constraint to the consumer's problem. With the gold capital denoted by k_{Gt}, and with the nominal price of the gold capital denoted by P_{Gt}, this constraint is written as

$$\alpha M_t = P_{Gt} k_{Gt}. \tag{34}$$

The consumer now divides goods output between consumption of goods, investment in oil, investment in standard capital, and investment in gold capital, denoted by i_{Gt}. With δ_G denoting the depreciation rate, the gold investment is given by

$$i_{Gt} = k_{Gt+1} - k_{Gt} \left(1 - \delta_G\right). \tag{35}$$

In terms of the allocation of resources, the consumer now additionally spends time working for the gold firm, denoted by l_{Gt}, so that the time constraint is

$$1 = x_t + l_t + l_{Gt} + l_{Ot}. \tag{36}$$

The consumer rents capital to the gold firm, with share denoted by s_{Gt}, so that the shares add to one:

$$s_t + s_{Ot} + s_{Gt} = 1. \tag{37}$$

The consumer invests in the equity stock of the gold producer and receives dividends for this each period. With the value per share denoted by V_{Gt}, the dividends denoted by D_{Gt}, and the share of the stock ownership denoted by z_{Gt}, the time t stock investment plus dividend is given by $-V_{Gt}(z_{Gt+1} - z_{Gt}) + D_{Gt}z_{Gt}$. The consumer rents out capital and labor to the gold producer, as in the oil problem.

The gold producer has the technology

$$i_{Gt} = (l_{Gt}h_t)^{\phi_1}(s_{Gt}k_t)^{\phi_2}F_{Gt}^{1-\phi_1-\phi_2}, \tag{38}$$

with the dividend D_{Gt} given by

$$D_{Gt} = P_{Gt}(l_{Gt}h_t)^{\phi_1}(s_{Gt}k_t)^{\phi_2}F_{Gt}^{1-\phi_1-\phi_2} - P_tw_tl_{Gt}h_t - P_tr_ts_{Gt}k_t. \tag{39}$$

It is assumed that the firm which produces the gold investment, faces the same fixed factor (gold mines), competitive markets, and CRS production technology conditions as the oil production firm. The gold firm's problem is to maximize the value $D_{Gt} + V_{Gt}$ with respect to labor and capital inputs, l_{Gt} and s_{Gt},

$$\max_{\{s_{Ot}, l_{Ot}\}_{t=0}^{\infty}} \sum_{s=t}^{\infty} \left[\frac{P_{Gs}(l_{Gs}h_s)^{\phi_1}(s_{Gs}k_s)^{\phi_2}F_{Gs}^{1-\phi_1-\phi_2} - P_sw_sl_{Gs}h_s - P_ss_{Gs}k_s}{\prod\limits_{j=t}^{s}\left(1+R_j\right)} \right]. \tag{40}$$

Given the CRS technology, profit maximization implies,

$$D_{Gt} + V_{Gt} = \sum_{s=t}^{\infty} \left[\frac{\phi P_si_{Gs}}{\prod\limits_{j=t}^{s}\left(1+R_j\right)} \right]. \tag{41}$$

The consumer budget constraint is now

$$P_tf\left([1 - s_{Ot} - s_{Gt}]k_t, i_{ot}, [1 - x_t - l_{Ot} - l_{Gt}]h_t\right) + P_tw_th_t\left(l_{Ot} + s_{Ot}\right) + P_tr_tk_t\left(s_{Ot} + s_{Gt}\right)$$

$$+ D_{Ot}z_{Ot} + D_{Gt}z_{Gt} + H_t$$

$$= P_tc_t + M_{t+1} - M_t + B_{t+1} - (1+R_t)B_t + P_t\left(k_{t+1} - k_t\left(1-\delta\right)\right) + P_{Ot}i_{ot}$$

$$+ P_{Gt}\left(k_{Gt+1} - k_{Gt}\left(1-\delta_G\right)\right) + V_{Ot}(z_{Ot+1} - z_{Ot}) + V_{Gt}(z_{Gt+1} - z_{Gt}). \tag{42}$$

and the consumer problem is to maximize utility in Eq. (1) with respect to $c_t, x_t, s_{Ot}, l_{Ot}, k_{t+1}, i_{ot}, M_{t+1}, B_{t+1}, z_{Ot+1}$, plus the additional variables $z_{Gt+1}, k_{Gt+1}, s_{Gt}$, and l_{Gt}, subject to Eqs. (6), (34) and (42).

Defining $p_{Gt} = P_{Gt}/P_t$, the first-order conditions now add the equation,

$$\frac{p_{Gt+1}\left[v_{t+1}/\lambda_{t+1} + 1 - \delta_G\right]}{p_{Gt}} = 1 + r_{t+1} - \delta \tag{43}$$

which implies that, in equilibrium, the return to investment in gold capital must equal the real return on investment in standard capital. The return to investment in gold is the relative shadow value of the reserve constraint (34), $p_{Gt+1}v_{t+1}/\lambda_{t+1}$, plus the capital gain net of depreciation $\left(1-\delta_G\right)p_{Gt+1}$.

The additional asset price equation for the gold stock price is given by

$$\frac{V_{Gt+1} + D_{Gt+1}}{V_{Gt}} = 1 + R_{t+1}. \tag{44}$$

Given a flexible price of gold, the price of gold will rise at the rate of inflation, as follows in parallel fashion from Proposition 1. Assuming in contrast that the nominal price of gold is rigid at $\bar{P}_{Gt}$, the

implied gold price change from one regime to the next is given by $\bar{P}_{Gt+1}/\bar{P}_{Gt} = (R_{t+1} - g_{t+1})/(R_t - g_t)$, as follows in parallel fashion from Proposition 2.

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