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Abstract

The advent of shale oil in the United States triggered a structural transformation in the oil market. We show, both theoretically and empirically, that this process has relevant consequences on oil risk premia. We construct a consumption-based model with shale producers interacting with financial speculators in the futures market. Compared to conventionals, shale producers have a more flexible technology, but higher risk aversion and additional costs due to their reliance on external finance. Our model helps to explain the observed pattern of aggregate hedging by US firms in the last decade. The empirical analysis shows that the hedging pressure of shale producers has become more relevant than that of conventional producers in explaining the oil futures risk premium.

JEL classification: G00, G13, G32, Q47.

Keywords: shale oil, futures, risk premium, hedging, speculation, limits to arbitrage.

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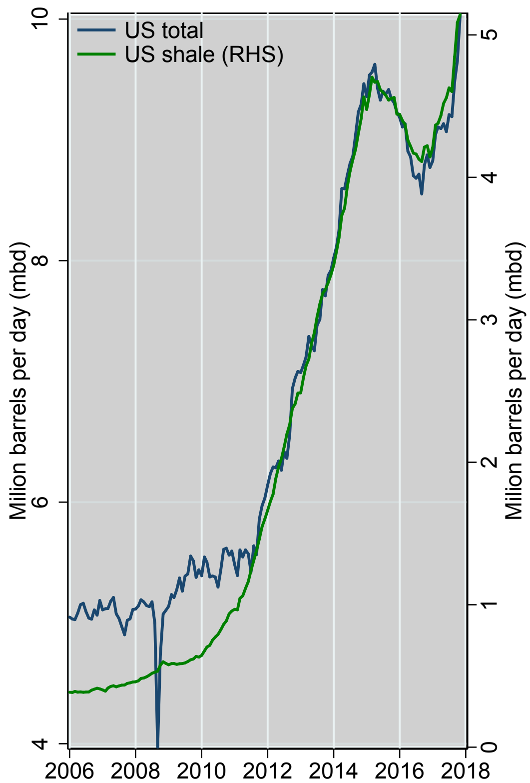
1 Introduction

The advent of shale oil has radically altered the supply of crude oil in the United States and its effects have reverberated across the global oil market. Between 2006 and 2018, the US has almost doubled its crude oil production becoming the second largers world producer, mostly on account of the output from shale wells (Figure 1.1, left panel). The advent of shale technology has introduced relevant changes in the oil production sector, on both the technology and financing sides. Fracking and horizontal drilling allow shale producers to respond more quickly to oil price changes; however, the adoption of the new technology required a massive expansion in capex and exploration which was accompanied by an increasing amount of debt in the oil sector (Figure 1.1, right panel).

While a growing literature explores the impact of the shale revolution on the economy, the technology and financing features of the shale sector are rarely considered jointly, as well as their effects on oil prices within a unified modelling framework. In this paper we consider both technology and financing characteristics of shale producers to explore the production-price nexus. In particular, we document how the advent of shale oil has impacted oil prices through the producers' supply and hedging pressure. Our analysis is both theoretical and empirical. First, we introduce shale producers in a consumption-based model of crude oil, in which prices are determined in equilibrium from the interaction between producers and speculators in the oil futures market, following Acharya et al. (2013) (ALR henceforth). Our model shows that the peculiar characteristics of shale producers, both in terms of technology and financing structure, matter in equilibrium. Second, we empirically examine the drivers of the risk premium embedded in WTI futures contracts before and after the advent of shale oil. By separately identifying conventional and shale producers in the US oil industry, we show that US shale companies have become one relevant driver of global spot and futures prices.

Our producer-speculator model is designed as follows. Risk-averse producers hedge future profits by storing inventories and selling futures contracts; speculators, who buy futures as counterpart of producers and lend money to producers, are capital constrained so there are limits for the hedging demand of producers to be satisfied (limits-to-arbitrage friction). The model has two periods and oil producers are shale producers: with respect to conventional producers, they are modeled as more flexible in their supply decisions but with higher risk aversion and additional production costs due to their reliance on external finance. Compared to the conventional producer vs. speculator model, the limits-to-arbitrage friction is amplified because: (1) a higher risk aversion of shale firms generates a higher hedging pressure raising the futures risk-premium, i.e. the difference between



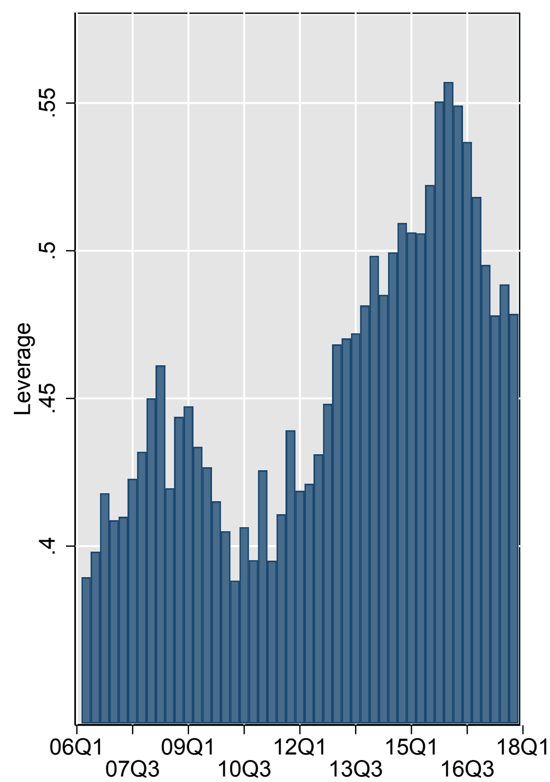


Figure 1.1: US oil production and leverage. The left plot displays the total US crude oil production and shale oil production measured in terms of milion barrels per day (mbd); both series are from EIA. Shale-oil production includes hydraulically fractured production originated from EIA plays: Monterey, Austin Chalk, Granite Wash, Woodford, Marcellus Haynesville Niobrara-Codell, Wolfcamp, Bonespring, Spraberry, Bakken, Eagle Ford, and Yeso-Glorieta. The right plot displays median leverage defined as total liabilities/total assets for US E&P companies with SIC code 1311.

expected spot prices and current futures prices (*risk aversion effect*) and (2) a more flexible supply schedule reduces the quantity to be hedged but, in equilibrium, also raises the variance of spot and futures prices thereby leading to a higher futures risk premium (*technology effect*).[1] A comparative simulation of the shale-speculator and conventional-speculator models reveals that in an oil sector populated by shale producers the demand for financial hedging might be higher, beacause of higher risk aversion, or lower mainly because of a *cost effect* (non-negligible operational costs erode producer's expected profits, reducing the amount of production to be hedged).

Using a novel hand-collected firm-level dataset with detailed information on financial

[1]This effect is related to the fact that the model is two-period and oil supply is finite, so must be interpreted as a long-run effect.

hedging contracts, we calibrate our model to replicate the aggregate dynamics of hedging by US oil companies in the last decade. The simulation captures both the surge in aggregate hedging before 2013 and the marked fall in 2014-15 following the oil price decline. Moreover, we empirically investigate the role of US producers in driving the futures risk premium. Measures of producer's default risk, to proxy for the fundamental hedging pressure, are computed from firm-level balance sheet data obtained from the Compustat database. In particular, we distinguish conventional and shale producers on the basis of the rate of growth in their ouput, assuming that producers with the fastest expansion in production are also those adopting the new technology. We then regress the futures risk premium on the default risk specific to conventional and shale producers, controlling for time-varying risk absorption capacity of speculators and their commodity-related exposure.

We show that, in the last two decades, the default risk of shale producers has indeed become a more relevant driver of the futures risk premium, reflecting the recomposition of the oil industry. In this perspective, our results suggest that the shale revolution has brought back producers at the heart of the price discovery mechanism. However, this increased hedging pressure on the part of producers found a substantial offset from a corresponding expansion of speculative capital on the long side, which thereby curbed the fluctuations in the risk premium component of the futures price. To account for the time-varying risk absorption capacity of speculators, who take the long side of the oil futures, we build an indicator of U.S. banks activity in commodity derivatives. This measure captures *directly* banks' off-balance (notional) exposure and is measured in relation to banks' trading assets. According to this measure, U.S. banks ability to engage in derivatives markets remained substantial also in the last decade, at a time when other measures of speculator capital constraints, such as the one based on broker-dealer balance sheet have instead fallen dramatically.

The paper is organized as follows. Section 2 reviews the theoretical and empirical contributions related to our study. Section 3 explains the theoretical model, and Section 4 comments on the main predictions obtained via model simulation. Section 5 proposes an empirical validation of the model looking at the effect of producers' default risk on futures risk premium. Section 6 concludes.

2 Literature review

A growing literature investigates the impact of the shale revolution on U.S. production and the economy. With respect to conventional producers, shale firms have different technology and financing structure. On the one hand, greater drilling responsiveness and higher productivity from unconventional wells have the potential to magnify the price response of US production (Newell and Prest, 2017). Bjørnland et al. (2017) use well-level data from North Dakota – a region that has recently gained a crucial relevance for the overall US unconventional production – and show that firms using shale oil technology are more flexible in allocating output intertemporally, thus suggesting a production pattern more consistent with the Hotelling's theory of optimal extraction. Anderson et al. (2018) recast the traditional Hotelling's model as a drilling problem and present a similar outcome using detailed well-level data from Texas. However, they find only drilling activity to respond dynamically to price incentives while production, being constrained by decaying reservoir pressure, exhibits a more limited price responsiveness.

Domanski et al. (2015) document how the shale boom was financed by a rapid increase in debt in the U.S. oil and gas producing sector. This expansion occurred in a period of historically low interest rates with fairly stable oil prices positively affecting the value of oil reserves, i.e. the firms' main source of collateral to access external funds. This buildup in leverage was not inconsequential for producers: according to Gilje et al. (2017) it materially affected firms' output and investment decisions, with firms potentially sacrificing long run project value, and could ultimately have made the oil market more exposed to financial shocks (Dale, 2015).

Few papers study the price effects of the shale revolution. Belu Manescu and Nuño (2015) employ the general equilibrium model proposed in Nakov and Nuño (2013) to assess the impact of shale production on global oil prices, finding that price effects are muted by the contraction in non-shale oil supply, largely from Saudi Arabia. Via counterfactual analysis Kilian (2017) investigates the effect of the shale revolution on Arab oil producers and finds a marginal impact of the fracking boom on global oil prices and the 2014-15 oil slump. A similar finding is presented in Baumeister and Kilian (2016) who construct price forecasts for oil spot prices using a VAR model, finding that global supply factors (among which the shale revolution) are only partially responsible for the 2014 price decline. Bornstein et al. (2017) construct a general equilibrium model of the oil sector with OPEC and non-OPEC producers: by including fracking producers with more flexible technology and shorter lags between investment and production, they argue that oil price volatility is bound to decline.

Some papers investigate other aspects linked to the advent of shale oil. Gilje (2017) proposes an identification strategy based on shale oil discoveries to examine how changes in local credit supply affect the real economy. Hunt et al. (2015) examine the macroeconomic impacts of the shale revolution and their effects for the US economy both in terms of GDP and the trade balance. Kilian (2016) describes how increasing shale production led to the oil glut in Cushing and widened the Brent-WTI spread in 2011. Gilje et al. (2016) use news on US shale production to measure the spillovers of shale technology shocks on global equity prices, detailing different transmission channels from the oil industry to other productive sectors.

Our model investigates the shale market from a broader asset pricing perspective, including both the financing and technology features of shale production, and drawing micro-founded predictions for equilibrium spot and futures prices. In this perspective, we show via simulation that our framework can accommodate two optimal risk management theories predicting opposite hedging behavior of firms. On the one hand, in good states less-capitalized shale firms hedge more than conventional firms due to a higher risk of default, coherently with Froot et al. (1993). On the other hand, in bad states the expected profits of shale firms can be so low – due to high debt burdens and decreasing net worth levels – that their hedging demand is lower than that of well-capitalized conventional producers. This last effect occurs as a consequence of collateral constraints affecting the dynamic trade-off between external financing and risk management, as predicted by modern theories of risk management (see Rampini and Viswanathan, 2010 and Rampini et al., 2014). As pointed out by Mello and Parsons (2000) every hedging strategy comes packaged with a borrowing strategy: suggestive evidence of a tight link between between credit and hedging decisions can be found in many 10-K filings of oil and gas companies. For example, according to Carrizo Oil and Gas Inc. *"The Company uses only credit agreement participants to hedge with, since these institutions are secured equally with the holders of the Company's bank debt (2015)"*. Our model incorporates this sector specific feature, as shale producers who engage in futures trading with speculators also borrow from based on their reserves (so called "reserves based lending"; Azar, 2017).

3 Model

In this Section we introduce shale producers in a consumption-based model of crude oil, in which oil prices are determined in equilibrium from the interaction between producers and financial speculators. We first characterize the agents in the economy; then, we model an economy in which producers are only shale companies.

3.1 The agents in the economy

Our framework is a consumption-based model with two periods and three agents: a representative consumer, the manager of an oil producing firm and the manager of a financial institution investing in oil futures. The interaction between risk averse producers and capital constrained speculators gives rise to a limits-to-arbitrage friction that impacts equilibrium oil prices.

The commodity consumers' inverse demand function is given by:

$$S_t = \omega \left(\frac{C_t}{Q_t} \right)^{1/\epsilon}$$

where S_t is the commodity spot price, Q_t is the equilibrium commodity supply, C_t is the consumption of other goods, and ω and ϵ are positive constants. The inverse demand function can be derived from a representative consumer with CES preferences over two goods, a consumption good (C) and oil (Q) with an intratemporal elasticity of substitution equal to ϵ. The consumption C_t, which in the model represents an exogenous demand shock, is distributed lognormally with

$$E[lnC_t] = \mu \qquad \text{and} \qquad Var[lnC_t] = \sigma_c^2$$

In the following we introduce two types of producers, a conventional and a shale producer, and a financial institution (speculator) which does not only invest in the futures market but also provides credit to producers. In the next section, we compute the equilibrium of a shale-speculator model (i.e., an economy in which producers are only shale companies) and evaluate comparative statics with respect to a model featuring only conventional (instead of shale) producers and "pure speculators" in the futures market (i.e., investors in commodity futures with no lending activity). For further details on the latter, see ALR.

Oil producers. Production firms are run by risk-averse managers who aim at smoothing profits over time. For this purpose, they store oil inventories and sell futures contracts to hedge against low prices (so low profits) next period. When aggregate demand shocks hit the economy, producers choose the quantity of inventories and futures contracts that maximize their risk-adjusted profits.

Oil companies can be of two types: conventional (p) or shale (s). Conventional firms have a predetermined production schedule which allows them to extract precisely g_t in each period. At time t, they save an amount i_t^p from current supply, with current output given by

$$q_t^p = g_t - i_t^p$$

At the same time, they hedge an amount h_t^p of next period output in the futures market. The model has two periods $t = 0, 1$. Denoting the consumer's frictionless stochastic discount factor[2] as Λ_t, profits as π_t^p, the coefficient of relative risk aversion of the conventional firm's manager as γ^p, and the price of futures contracts as F_t, the problem of the conventional producer is[3]

$$\max_{\{i_0^p, h_0^p\}} \pi_0^p + E_0(\Lambda_1 \pi_1^p) - \frac{\gamma^p}{2} Var_0(\pi_1^p)$$

with profit function

$$\pi_0^p = S_0(g_0 - i_0^p) \quad (3.1)$$

$$\pi_1^p = S_1(i_0^p + g_1) + h_0^p(F_0 - S_1) \quad (3.2)$$

and subject to the constraint

$$q_0^p \leq g_0 \Longleftrightarrow i_0^p \geq 0 \quad (3.3)$$

Shale producers have different preferences, profits and technology. Their salient characteristics are incorporated through the following assumptions:

1 As to prefences, being structurally less capitalized, shale producers are modelled as more *risk averse* than conventionals: indeed, companies heavily relying on external financing are more exposed to shocks than capitalized companies, and this affects their price of risk. This assumption is motivated by an extensive literature on the costs of external financing as one of the key determinants of fundamental hedging demand by risk averse managers (Froot et al., 1993; Gilje, 2016). In modelling terms, we assume that the shale producer's risk aversion satisfies

$$\gamma^s > \gamma^p \quad (3.4)$$

[2]The one prevailing under the assumption of no frictions.

[3]Without loss of generality, we assume that the one-period depreciation rate of oil inventories is zero or, more generally, that there are no storage costs.

2 Thanks to the new technology of horizontal drilling, they can extract (and sell) oil from reserves which would be otherwise, i.e. with conventional vertical drilling, unavailable for current production. Put differently, shale producers bear an *option* to depart from the predetermined production schedule $\{g_0, g_1\}$ and extract an amount e_0^s from next period supply, g_1, so that current output reads

$$q_0^s = g_0 - i_0^s + e_0^s$$

3 Holding this option-like technology has non-negligible (relatively to conventional producers) *operational costs* related to installation of facilities, drilling, and transportation equipment, that shale producers need to pay upfront. In the model, the technology investment has a fixed cost[4]

$$D_0$$

which is financed externally by capital constrained speculators. Consistent with a specific feature of debt financing in the shale oil sector, D_0 is collateralized on the value of current reserves, $S_0 g_0$[5]. Debt is paid back at time 1, and the interest-rate charged is the risk-free rate r. If the collateral value is lower than the amount granted, however, that is

$$D_0 > S_0 g_0$$

shale producers also incur an extra payment in term of oil barrels detracted from next period supply (by the speculator). In presence of this *collateral constraint*, next period output reads

$$q_1^s = g_1(1 - \psi) + i_0^s - e_0^s$$

where $\psi \in [0, 1)$ is set exogenously in such a way that the speculator's expected revenues from the sale of shale oil offset the current losses from credit[6].

[4] where $D_0 > 0$ is a structural parameter indicating the total operational costs.

[5] Producers need to pledge g_0 as collateral for the loan, as g_0 can be considered as *proved reserves*. Proved reserves are valued 100% of their market value, from which the choice of the collateral value. Our model is an obvious simplification of the complex reserve based lending agreements between producers and lenders, which also distinguish between producing and non producing reserves, as well as developed and undeveloped ones.

[6] That is, ψ is such that

$$D_0 - S_0 g_0 = \psi E_0[\Lambda_1 S_1 g_1] \qquad \text{with} \quad D_0 > S_0 g_0$$

which implies

$$\psi = \frac{[D_0 - S_0 g_0]^+}{E_0[\Lambda_1 S_1 g_1]}$$

The problem of the representative shale producer can be simplified to

$$\max_{\{x_0^s, h_0^s\}} \pi_0^s + E_0(\Lambda_1 \pi_1^s) - \frac{\gamma^s}{2} Var_0(\pi_1^s)$$

where $x_0^s = i_0^s - e_0^s$ and necessarily[7]

$$q_0^s \leq g_0 + g_1 \Longleftrightarrow x_0^s \geq -g_1 \tag{3.5}$$

Shale producer's profit function reads

$$\begin{aligned} \pi_0^s &= S_0(g_0 - x_0^s) \\ \pi_1^s &= S_1[x_0^s + g_1(1-\psi)] + h_0^s(F_0 - S_1) - D_0^{S_0}(1+r) \end{aligned}$$

where from the previous discussion

$$D_0^{S_0} = \min(D_0, S_0 g_0), \quad \psi = \frac{[D_0 - D_0^{S_0}]}{E_0[\Lambda_1 S_1 g_1]} \tag{3.6}$$

To sum up, shale producers have a higher gamma than conventional producers (Assumption 1), a relaxed technology constraint (Assumption 2) and a state-contingent liability (Assumption 3). In case of zero operational costs ($D_0 = 0$), external financing is not needed so the shale producer problem collapses to that of a conventional producer with a more flexible technology and a higher risk-aversion.

Speculators. Financial institutions (indexed by f) are speculators in the oil futures market and creditors to shale producers. They are ruled by risk-neutral managers and subject to capital constraints that are proportional to the variance of time 1's profits.[8] At time 0, the financial institution lends D_0 to the shale producer and choose the optimal number of long positions h^f in the crude oil futures market. The speculator's objective function

where we set D_0 such that $\psi \in [0, 1)$, i.e. shale producers' total profits are never fully absorbed by debt.

[7] As i_0^s, e_0^s are linearly dependent state variables, any linear combination of the two will yield the same FOC for the producer problem. We choose $x_0^s = i_0^s - e_0^s$ so that when $x_0^s > 0$ ($x_0^s < 0$), the producer is saving (extracting) oil barrels for next period output (current output).

[8] This formulation is observationally equivalent to the case of a risk-averse manager with no capital constraints.

reads

$$\max_{h_0^f} \pi_0^f + E_0(\Lambda_1 \pi_1^f) - \frac{\gamma^f}{2} Var_0(\pi_1^f)$$

with profit function

$$\pi_0^f = -D_0$$

$$\pi_1^f = h_0^f(S_1 - F_0) + D_0^{S_0}(1+r) + \psi g_1(S_1)$$

"Pure speculators" share the same characteristics of the financial instituions described above; however, their business is limited to investing in commodity futures, with no lending activity. Hence, their profit function reduces to $\pi_0^f = 0$ and $\pi_1^f = h_0^f(S_1 - F_0)$.

3.2 Optimization of the producer

We assume that the oil sector is populated by shale producers only, and imagine an economy composed by consumers, shale producers and financial institutions accommodating both producers' hedging and borrowing needs. From the shale producer problem, the FOCs with respect to x_0^s and h_0^s yield

$$\hat{x}_0^s = \frac{-S_0 + E_0(\Lambda_1 S_1) + \lambda^s}{\gamma^s \sigma^2} - g_1(1-\psi) + \hat{h}_0^s \tag{3.7}$$

and

$$\hat{h}_0^s = g_1(1-\psi) + \hat{x}_0^s - \frac{E_0[\Lambda_1(S_1 - F_0)]}{\gamma^s \sigma^2} \tag{3.8}$$

where λ^s is the shadow price of the stock-out constraint for the shale producer, i.e.

$$x_0^s \geq -g_1 \tag{3.9}$$

and σ^2 is the variance of the spot price.[9] Note that $\hat{x}_0^s$ $\left(\hat{h}_0^s\right)$ depends negatively (positively) on γ^s, meaning that the higher risk aversion of shale producers with respect to

[9] As consumption is assumed to be lognormal with parameters μ and σ_c, in partial equilibrium the spot price is also lognormal

$$S_t \sim \log N\left(\frac{\mu}{\epsilon} + \log\left(\omega Q_t^{-\frac{1}{\epsilon}}\right), \frac{\sigma_c}{\epsilon}\right)$$

with mean

$$E_0(S_1) = \omega Q_1^{-\frac{1}{\epsilon}} e^{\frac{\mu}{\epsilon} + \frac{1}{2}\left(\frac{\sigma_c}{\epsilon}\right)^2}$$

conventional producers predicts a *lower* desired quantity of oil barrels to carry over and a *higher* desire of hedging future sales. At the same time, $\hat{x}_0^s$ $\left(\hat{h}_0^s\right)$ depends positively (negatively) on the liability term ψ, meaning that the higher borrowing needs of shale producers with respect to conventional producers predict a *higher* desired quantity of oil barrels to carry over and a *lower* desire of hedging future sales. In particular, it is interesting to note that the collateralized debt financing in the shale oil sector has an important effect on the producers' risk-management decisions: when the debt cost D_0 is high with respect to the value of proven reserves $S_0 g_0$, i.e. $\psi > 0$, shale producers are forced to give up a share of their next period supply as an additional cost for undercollateralized loans. As a consequence, they face a lower quantity of risk to hedge, which entails a lower hedging pressure.

Combining (3.7) and (3.8) yields an expression for futures prices as a function of the spot price

$$F_0 = (S_0 - \lambda^s)(1 + r) \tag{3.10}$$

where $(1 + r) = 1/E_0[\Lambda_1]$ is the gross one-period risk-free rate and λ^s accounts for the *convenience yield* of holding oil the spot at time 0, following the definition of the basis as in ALR.[10] It is worth noting that, in our setting, the convenience yield arises from a different (relaxed) stock-out constraint

$$q_0^s \leq g_0 + g_1 \Longleftrightarrow x_0^s \geq -g_1 \tag{3.11}$$

instead of the original one

$$q_0^p \leq g_0 \Longleftrightarrow i_0^p \geq 0 \tag{3.12}$$

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and variance

$$Var_0(S_1) = \sigma^2 = \omega^2 Q_1^{-\frac{2}{\epsilon}} \left(e^{\left(\frac{\sigma_c}{\epsilon}\right)^2} - 1\right) e^{\frac{2\mu}{\epsilon} + \left(\frac{\sigma_c}{\epsilon}\right)^2}$$

In equilibrium, the variance of the spot price σ^2 depends negatively on Q_1^*, so on x_0^*.

[10] The basis is defined as

$$\frac{S_0 - F_0}{F_0} = y - \frac{r + \delta}{1 - \delta}$$

where y is the *convenience yield* of holding oil barrels at time 0, and δ is the cost of storage (which we normalize for simplicity to 0). Combining this expression with equation 3.10, one gets an explicit relation between y and the shadow price λ as

$$y = \frac{\lambda}{S_0} \frac{1 + r}{1 - \delta}$$

Note that the risk-free rate, i.e. the rate at which consumers discount future consumption, is constant because of the joint assumption of CES preferences, lognormal consumption and partial equilibrium.

That is, in our model one needs larger positive shocks in order for the convenience yield to be positive, as the stock-out constraint becomes binding only when the shale producer has run out of *all* of its oil reserves.

3.3 Optimization of the speculator

From the FOC of the financial institution one gets

$$\hat{h}_0^f = \frac{E_0[\Lambda_1(S_1 - F_0)]}{\gamma^f \sigma^2} - \psi g_1 \tag{3.13}$$

The tighter the capital constraint γ^f, the *lower* the number of futures contracts the speculator can afford. At the same time, the higher the oil price risk to which next period profits are exposed (induced by the shale producers' liability term ψ), the *lower* the number of futures contracts the speculator is willing to hold.

3.4 Equilibrium results

The equilibrium solution for x and h can be found by applying the condition of zero net supply of futures contracts

$$h_0^s = h_0^f \tag{3.14}$$

By recalling (3.8) and (3.13), we observe that a drop in producers' hedging pressure generated by $\psi > 0$ is perfectly offset by an equivalent drop in speculators' appetite for futures contracts. As a consequence, *producers' borrowing needs and the degree of collateralization have no role in shaping equilibrium prices*. The (expected) futures risk premium is

$$E_0\left[\frac{S_1 - F_0}{F_0}\right] = -(1+r)\text{Corr}_0(\Lambda_1, S_1)Std_0(\Lambda_1)\frac{\sigma}{F_0} + \frac{\gamma^f \gamma^s}{\gamma^f + \gamma^s}(1+r)\sigma^2\frac{Q_1}{F_0} \tag{3.15}$$

with

$$F_0 = (S_0 - \lambda^s)(1+r) \tag{3.16}$$

With respect to the one obtained in a conventional producer - pure speculator model, the futures risk premium has a higher risk aversion parameter $\gamma^s \geq \gamma^p$ (Assumption 1) and a relaxed stock-out constraint $\lambda^s \leq \lambda^p$ (Assumption 2). Next period (aggregate) output Q_1 is given by $Q_1 = x_0^* + g_1$, and the equilibrium quantity x_0^* is retrieved implicitly. The first term on the right-hand side is a *covariance component*, which depends on the correlation between the consumer's stochastic discount factor and the oil spot price, and the second one is the *limits-to-arbitrage component*. Combining the risk aversion of producers – which motivates the financial hedging pressure – with the capital constraint of speculators generates a *limits to arbitrage* friction: there are limits for the hedging demand of producers to be satisfied. Put it differently, the frictionless stochastic discount factor Λ_t is not the one which clears the futures market: the expected discounted payoff of a long futures position is greater than zero, reflecting the fact that speculators demand a compensation to fully accommodate producer's hedging needs.

These differences translate into three distinct effects on the futures risk premium, that can be rationalized into two categories, financing and technology effects:

- **Financing effects**:
  - <u>Risk-aversion effect</u>: the higher risk aversion of shale producers generates a higher hedging pressure that, for a given capital constraint of speculators, makes the futures risk premium *higher* than in the conventional-pure speculator world;
  - <u>Cost effect</u>: higher debt costs erode producers' future profits: a lower quantity of risk to hedge entails lower hedging pressures which is, however, perfectly offset by an equivalent drop in speculators' appetite for futures contracts: the risk premium in equilibrium remains *unchanged* at the conventional-pure speculator level.

- **Technology effect**: following a positive aggregate demand shocks, shale producers can boost production at time 0 which instead conventional producers are prevented from doing: this entails a lower quantity of next period supply to hedge but, in equilibrium, also a higher expected variance of spot and futures prices. The increased quantity of risk prevails, entailing a *higher* futures risk premium.

It is worth noting that, while the risk aversion effect exists no matter the aggregate demand of oil, the technology effect is state-contingent, and materializes only in times of high demand. Putting all these effects together, our model predicts a futures risk-premium in equilibrium which is always *positive* and *higher* than the one generated by an economy of only conventional producers.

4 Simulation

In this Section we simulate our model for two purposes. First, we compare the shale-speculator model with the conventional-pure speculator model: by doing so, we keep the same parameters for the two models except for the producer's risk aversion, and discuss comparative statics for temporary demand shocks of opposite sign. Second, we use historical spot prices as input to the model and generate a stream of predicted hedging ratios (i.e., the ratio between amounts hedged and oil supply) of the oil sector during the last 12 years, which we then compare with historical figures provided by our hand-collected dataset.

4.1 Calibration

In both simulations, the calibration is made as follows. Some parameters are chosen as in previous contributions: μ and σ_c are estimated from the time series of aggregate GDP growth; $\epsilon = 0.1$ and $\omega = 0.01$ are such that (1) the two goods are complement for the consumer, (2) the standard deviation of futures return is about 20 percent per quarter and (3) the share of oil expenditure on total expenditure on other goods is 10 percent.[11]
The predetermined supplies g_t are chosen such that the equilibrium spot price in response to a zero demand shock is equal to 1. The shale producers' debt D_0^s is set equal to the collateral value in presence of a zero demand shock, i.e. $D_0^s = S_0 g_0 = g_0$, while the conventional producers' debt D_0^p is set equal to 0. For illustrative purposes, we specify the shale producers' risk aversion parameter as $\gamma^s = \gamma^p(1 + \alpha)$, with α the representative fraction of shale oil in the market. In the simulation made in Section 4.2, we set $\alpha = 1$ and obtain $\gamma^s = 2\gamma^p$; in Section 4.3, we let α vary so to match the share of shale over total U.S. production in the last 12 years.

4.2 Comparative statics

We report model simulations for different levels of producer's risk aversion. Results from the shale-speculator model are reported in red, while those from the conventional-pure speculator model in black. The following figures display the optimal amount of hedging, inventories and the futures risk premium as functions of the producer risk aversion (namely, the fundamental hedging demand of the producer). The risk aversion coefficients of conventional and shale producers are displayed on a double x-axes (lower x-axis: γ^p, upper x-axis: $\gamma^s = 2\gamma^p$). For each model, we compare producers' responses

[11] See also the online Appendix of ALR.

Parameters	Values
μ	0.004
σ_c	0.02
ω	0.01
ϵ	0.10
g_0	0.63
g_1	0.63
D_0^s	0.63
D_0^p	0

Table 1: Parameter table.

to large positive and large negative demand shocks, corresponding to the 75th and 25th percentiles of the distribution of log consumption growth, respectively.

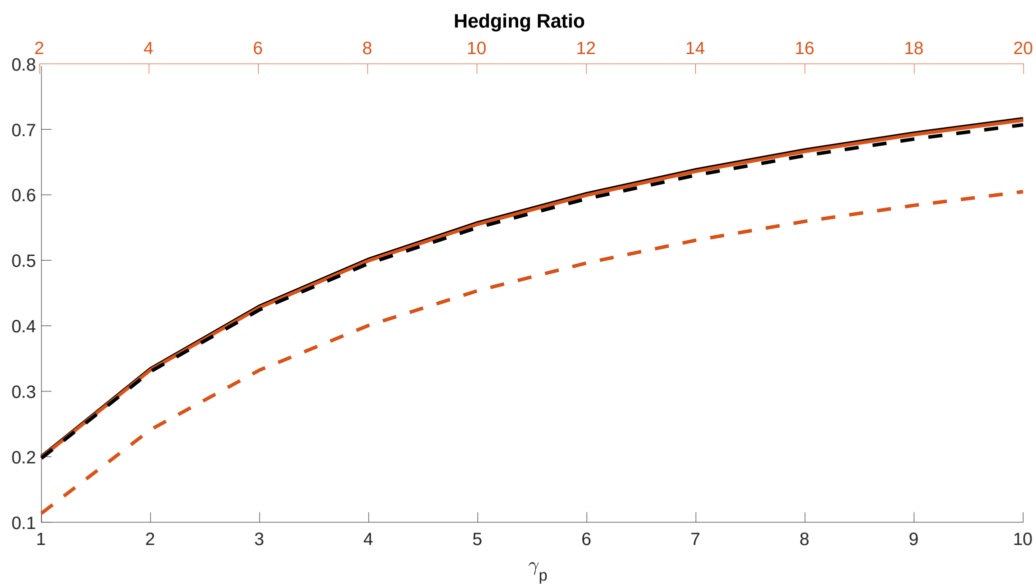


Figure 4.1: Model-implied hedging ratio of shale producers (solid and dashed red lines) and conventional producers (solid and dashed black lines). The lower (upper) x-axis: fundamental hedging demand of the conventional (shale) producer γ_p (γ_s). Solid lines result from large positive shocks which trigger the inventory constraint λ^p of the conventional producer, while dashed lines result from large negative shocks which trigger the collateral penalty ψ of the shale producer.

Figure 4.1 displays the model-implied hedging ratio of conventional producers and shale producers. Solid lines represent cases of large positive demand shocks, while dashed lines represent large negative demand shocks. In case of large positive shocks, the stock-out constraint λ^p binds for conventional producers but not for shale: by anticipating part of future supply, the latter have less oil to sell in the future so, in equilibrium, lower hedging needs (for same level of risk aversion) than conventionals. In case of large negative shocks, on the other hand, the borrowing constraint ψ binds for shale producers but never for conventionals: loan is undercollateralized so shale producers are forced to give up a fraction of future supply and have less oil to hedge than conventionals, thereby causing, again, lower hedging pressure. To sum up, both cost and technology effects do determine a lower hedging demand than conventionals; however, as the difference is almost negligible in case of positive shocks, it is very large in case of negative shocks. Note that, in order to finally assess whether shale producers hedge more or less than conventionals in equilibrium, it is important to also take into account the risk aversion effect: if the latter is material, hedging needs can be higher than those of conventional producers, more than offsetting the previous channels.

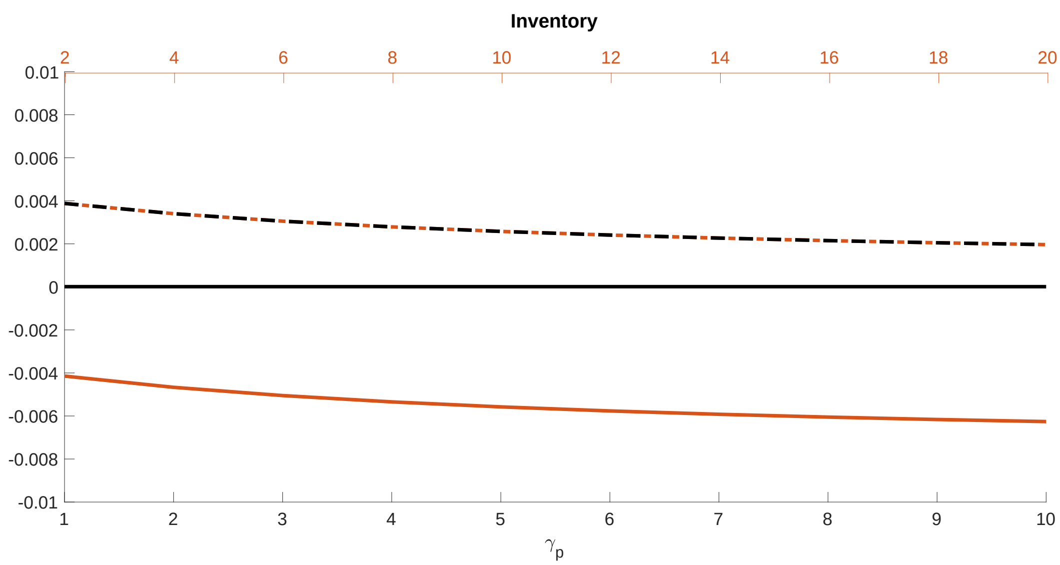


Figure 4.2: Model-implied optimal inventories of shale producers (solid and dashed red lines) and conventional producers (solid and dashed black lines). The lower (upper) x-axis: fundamental hedging demand of the conventional (shale) producer γ_p (γ_s). Solid lines result from large positive shocks which trigger the inventory constraint λ^p of the conventional producer, while dashed lines result from large negative shocks which trigger the collateral penalty ψ of the shale producer.

Figure 4.2 shows the optimal fraction of current reserves that producers carry over to increase next period output. Solid lines represent cases of large positive demand shocks, while dashed lines represent large negative demand shocks. In case of negative demand shocks, the stock-out constraints λ^p, λ^s are both slack and the producers hold equally profitable technologies. As a result, they wish to carry over the same number of oil barrels for next period output.[12] In case of large positive shocks, on the other hand, shale producers *exercise* their option-like technology by extracting oil from reserves otherwise designated to future production[13] - thereby showing in the figure as *negative* inventories - while conventional producers face a binding stock-out constraint.

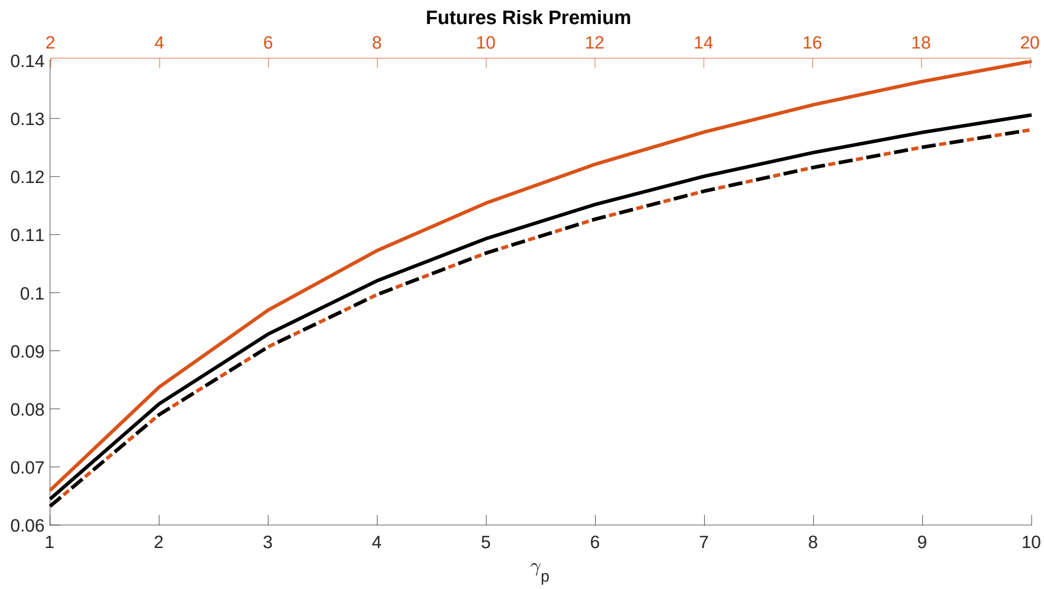


Figure 4.3: Model-implied futures risk premium of shale producers (solid and dashed red lines) and conventional producers (solid and dashed black lines). The lower (upper) x-axis: fundamental hedging demand of the conventional (shale) producer γ_p (γ_s). Solid lines result from large positive shocks which trigger the inventory constraint λ^p of the conventional producer, while dashed lines result from large negative shocks which trigger the collateral penalty ψ of the shale producer.

Figure 4.3 displays the equilibrium futures risk premium for conventional producers and shale producers. First of all, it is worth reminding that, independently of current demand levels, the risk-aversion effect induced by $\gamma^s > \gamma^p$ would always entail a higher futures risk premium for shale producers than conventional producers.[14] However, following a positive demand shock a second effect also comes into play, triggered by a fundamental difference in producers' stock-out constraints. With positive demand shocks, shale producers can boost production at time 0, unlike conventional producers: as observed from

[12] To be precise, shale producers' inventories are slightly higher due to the discussed marginal effect of the liability term ψ on $\hat{x}_0^s$, but the difference is negligible.

[13] Oil reserves unaccessible to conventional (vertical drilling) technologies.

[14] Follows immediately from the specification in Equation 3.15.

figure 4.1, this entails a slightly lower quantity of next period supply to hedge for shale producers but, in equilibrium, also a higher expected variance of spot and futures prices. The second effect of an increased quantity of risk prevails, entailing a *higher* futures risk premium for shale producers with respect to conventional producers. Following a negative demand shock, the liability term ψ comes into play generating a consistent drop in shale producers' hedging ratio (dashed red line in figure 4.1) and a negligible rise in shale producers' inventories (dashed red line in figure 4.2). As the former is offset by an equivalent drop in speculators' appetite for futures contract, the liability term ψ affects the futures risk premium only through the inventory channel, thereby generating the same negligible differences on the equilibrium outcome.

4.3 Model-implied and historical dynamics of the hedging ratio

In this Section we test the ability of our model to replicate the dynamics of financial hedging in the United States for different price levels. In particular, we construct the time series of aggregate hedging contracts held by the oil sector and compare it with the one obtained in equilibrium using the appropriate calibration of our model.

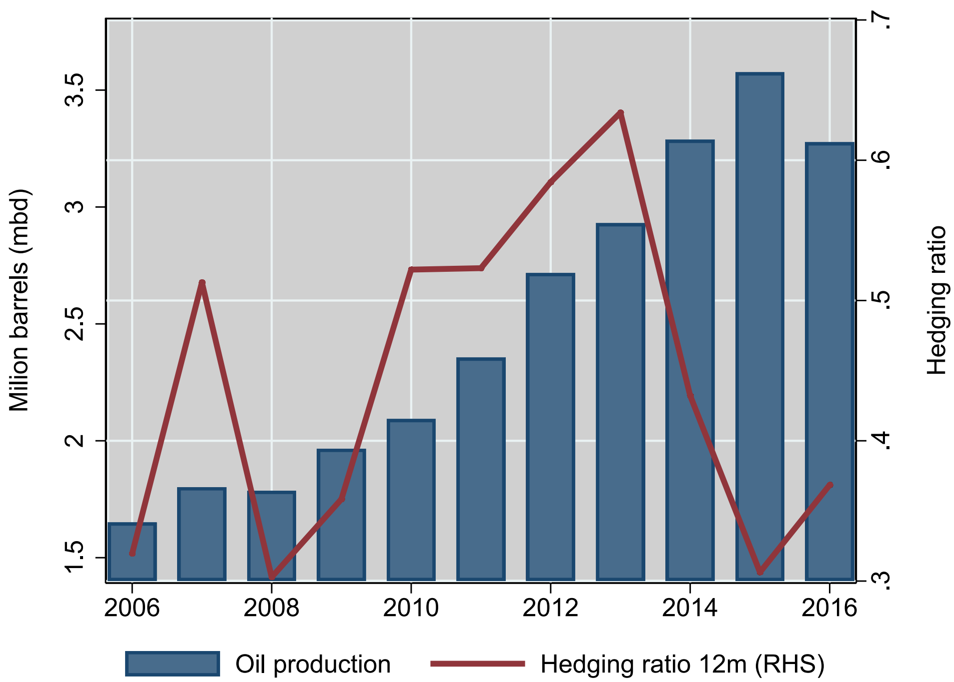


Figure 4.4: The graph displays total oil production of US E&P firms and the average value of their hedging ratio for their 12-month ahead crude oil production. Details on firms included in the sample of analysis are provided in Section 4.

To this end, we rely on a new hand-collected firm-level dataset providing detailed information on E&P hedging contracts used to hedge oil production during the period 2006-2016. The data set is constructed starting from annual company reports (10-K) available from the EDGAR website of the US Security Exchange Commission (SEC), and it provides information on the type of derivative instruments as well as on the notional amount of each hedging contract. We restrict the analysis to E&P companies with Standard Industrial Classification (SIC) code equal to 1311, which includes firms involved in "Crude Petroleum and Natural Gas" exploration and production activities.[15]

Our data set details the 12-month ahead hedging exposure of each company by type of instrument, and is richer than others employed in the literature. It consists of an unbalanced sample of 102 firms accounting for approximately 30% of overall US oil production and observed over an 11 years time period. The sectoral hedging measure is constructed by aggregating the value of all hedging contracts and summing across the whole sample of firms. Figure 4.4 displays the dynamics of the average 12-month ahead hedging ratio between 2006 and 2017 and the total oil production of firms included in our sample.

The model is simulated once for each quarter, calibrating the shock at each point in time to obtain the average WTI oil spot price observed over the same time span. Results are displayed in Figure 4.5. The model makes a good job in matching the amount of hedging contracts in the period of the shale boom: in particular, it captures the increase in hedging demand before 2013 and the fall thereafter.

5 Empirical estimates

The previous Section provided a theoretical underpinning for the link between futures risk premium, shale producers' fundamental hedging demand, and speculators' capital constraints. In this Section we empirically test this interplay and analyze how the recent recomposition in the oil industry has affected futures risk premia. Our exercise starts from the model equilibrium condition presented in Equation 3.15, and we estimate the following model as its empirical counterpart:

[15] We first retrieve from the Wharton database the full list of companies with SIC code equal to 1311. Then we filter out firms for which either the 10-k was not publicly available on EDGAR or the number of 10-k filings was smaller than five during the period 2006-2016. We further exclude smaller reporting companies that are not required to disclose information as their market risk is considered as negligible and firms where risk management activities cannot be reclassified in terms of quantitative data as they are essentially not reported in tabular form in item "7A. Quantitative and Qualitative Disclosures about Market Risk". Please notice that so-called "major companies" are not included in our final sample as they are generally classified with SIC code 2911 (Petroleum refining).

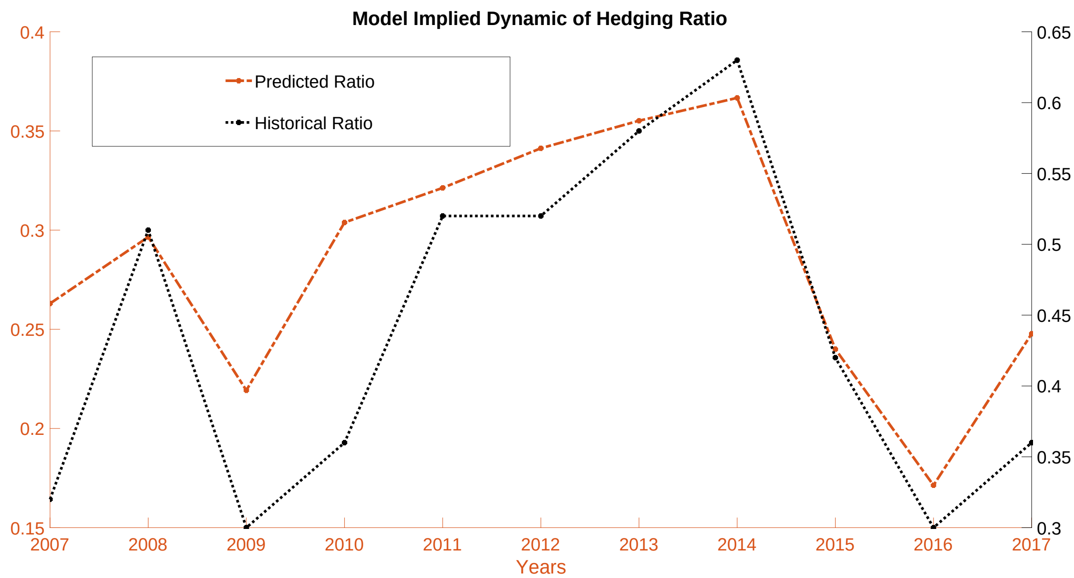


Figure 4.5: Historical hedging ratio (black line, right y-axis) and model-implied hedging ratio (red line, left y-axis).

$$FR_{t+1} = \alpha + \beta \, FHD_t + \delta \, Controls_t + u_{t+1} \tag{5.1}$$

where FR are crude oil excess returns on futures, FHD is our measure of fundamental hedging demand by producers, and $Controls$ are additional variables to account, among others, for the US business cycle and other characteristics of commodity markets at the time of the forecast; t denotes time measured in quarters. Similar to ALR we test model predictions by running forecasting regressions of crude oil futures returns, which represent our proxy for the futures risk premium. However, we restrict the analysis to oil prices and most importantly we split the sample into two periods to offer an accurate representation of the new producers emerged with the advent of the shale revolution. Indeed, while in the first part of the sample shale technology did not exist (or, at least, was not yet adopted in the oil sector), since the year 2000s shale producers – albeit at a slower pace – entered commodity markets. Therefore, to forecast risk premia in the second part of the sample, we estimate the following regressions:

$$FR_{t+1} = \alpha + \beta_1 \, FHDConv_t + \beta_2 \, FHDShale_t + \delta \, Controls_t + u_{t+1} \tag{5.2}$$

$$FR_{t+1} = \alpha + \beta_1\ FHDConv_t + \beta_2\ FHDShale_t + \beta_3\ SPcc_t + \delta\ Controls_t + u_{t+1} \tag{5.3}$$

where $FHDConv$ is the fundamental hedging demand of conventional producers, $FHDShale$ is that of shale producers and $SPcc$ is a measure of financial investors' capital constraints; provided that speculators invest not only in one asset class (as it is in the model), in the set of controls of Equation 5.3 we also include a measure of speculator preference for commodity futures, disregarded in standard oil regressions. In the following, we present additional details on the variables that are adopted in the empirical analysis.

5.1 Oil futures returns

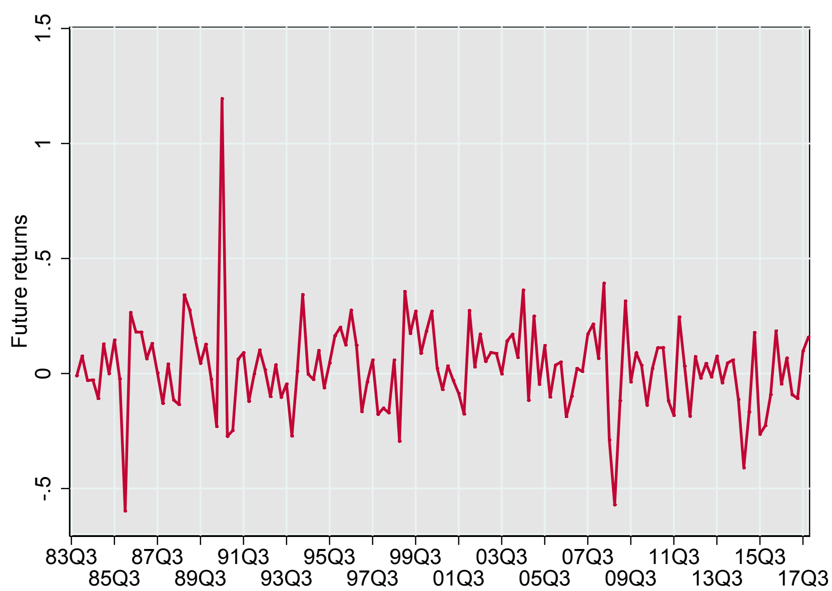


Figure 5.1: Time series of quarterly crude oil futures returns. Data come from the New York Mercantile Exchange (NYMEX) for the WTI Light Sweet Crude Oil contracts and are obtained from Bloomberg.

The variable FR is constructed using data from Bloomberg for the prices of WTI Light Sweet Crude Oil front month futures contracts quoted at the New York Mercantile Exchange (NYMEX). Following Gorton et al. (2013), we obtain 3-month rolling commodity futures excess returns as the one-month difference in the nearest to maturity contract, that would not expire during the next month, i.e. as:

$$\frac{F_{t+1,T} - F_{t,T}}{F_{t,T}} \tag{5.4}$$

where $F_{t,T}$ is the futures price at the end of each month t on the nearest contract, with expiration date T which is after month $t+1$, and $F_{t+1,T}$ is the price of the same contract at the end of month $t+1$. Quarterly returns are computed as the product of futures returns within each quarter. The quarterly series, starting in 1983Q3 due to data availability, is shown in Figure 5.1.

5.2 Producers' fundamental hedging demand

The fundamental hedging demand of producing firms is tightly linked to their distance to default. Following previous contributions, we proxy producers' fundamental hedging demand with a measure of sectoral default risk for the oil sector. For this purpose, we construct a balance sheet-based indicator by aggregating information from the financial statements of all US firms classified with SIC code 1311. For our analysis we proxy the default risk of oil producers with the Altman (1968) z-score, the most common accounting-based indicator of a company strength and financial conditions. We retrieve quarterly accounting data from Compustat for the whole period covering the availability of crude oil futures returns; our sample has a time varying composition due to sample attrition, but it consists on average of more than 200 oil producers per quarter. For each company, we construct the default risk measure $DefRisk$ by using the definition of the Altman (1968) z-score for manufacturing firms:

$$\begin{aligned} DefRisk = {} & 1.2 * (Working\,capital/Total\,assets) + 1.4 * (Retained\,earnings/Total\,assets) \\ & + 3.3 * (Ebit/Total\,assets) + 0.6 * (Market\,value\,of\,equity/Total\,liabilities) \\ & + 0.999 * (Sales/Total\,assets) \end{aligned} \tag{5.5}$$

The sectoral proxy for $DefRisk$ is obtained by taking the median value across firms in each quarter; a higher value of $DefRisk$ indicates a lower sectoral probability of default. We consider a unique indicator of $DefRisk$ during the period from 1983Q3 up to 2000Q1, using as a cut-off date the time in which data on shale production are recorded for the first time by the U.S. Energy Information Administration (EIA). Starting from 2000Q1 we compute two distinct measures of $DefRisk$, distinguishing between shale and conventional producers. However, establishing the precise nature of each producer does not represent a straightforward task, as data detailing the type of crude oil production technology are not available at the firm level.

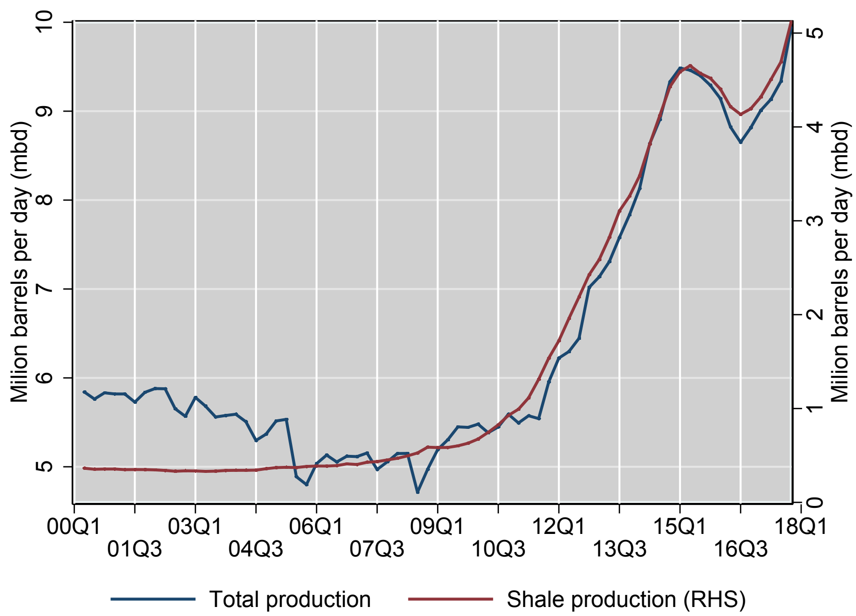


Figure 5.2: Time series of total and shale crude oil production in the US measured in mbd; both series are from EIA. Shale-oil production includes hydraulically fractured production originated from EIA plays: Monterey, Austin Chalk, GraniteWash,Woodford, Marcellus Haynesville Niobrara-Codell, Wolfcamp, Bonespring, Spraberry, Bakken, Eagle Ford, and Yeso-Glorieta.

To address this issue we propose an identification strategy that exploits the dynamics of crude oil production in the US, as reported in Figure 5.2. Since 2008-2009 total crude oil production has been trending up; the graph clearly shows how the increase was utterly driven by the upsurge in the shale oil production. In view of this evidence, we classify as shale producers those firms whose cumulated growth in production between 2009Q2 and 2017Q4 was higher than the median of the entire US oil sector in the same period. We consider the 2009Q2 as the beginning of the shale revolution, being the fourth quarter in a row in which shale production, highly volatile since then, accounted for at least 10% over total US crude oil production. In this way, we limit possible classification inconsistencies due to a marginally material and quite volatile shale production; other contributions in the literature propose a very similar starting date (see Kilian, 2017). Our classification of shale and conventional firms also extends to the pre-shale revolution period (i.e., since 2000Q1), meaning that oil companies that are classified as shale are assumed to be more active in shale than conventional production also between 2000 and 2009. This

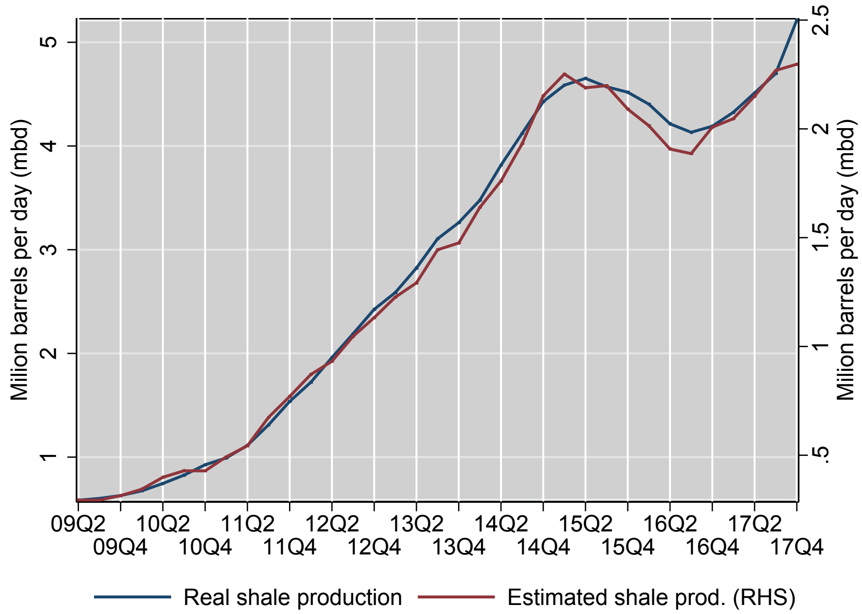


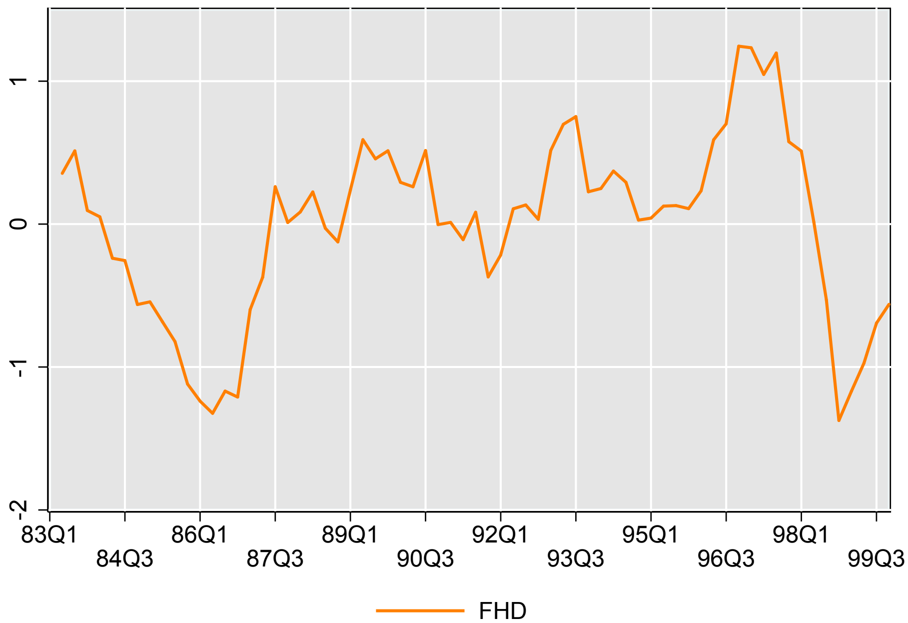
Figure 5.3: Time series of actual shale oil production retrieved from EIA and estimated shale oil production in the sample. Both series are measured in mbd; the estimated shale oil series is multiplied by a scaling factor equal to the quarterly fraction of shale crude oil over total US production.

seems reasonable provided that, in order to reach high levels of production, shale technology required, at the first stage, long periods of exploration and technology development. However, drilling from shale wells was obviously slow in the early 2000s, which explains why our identification based on production dynamics needs to rely only on data from 2009 onwards.

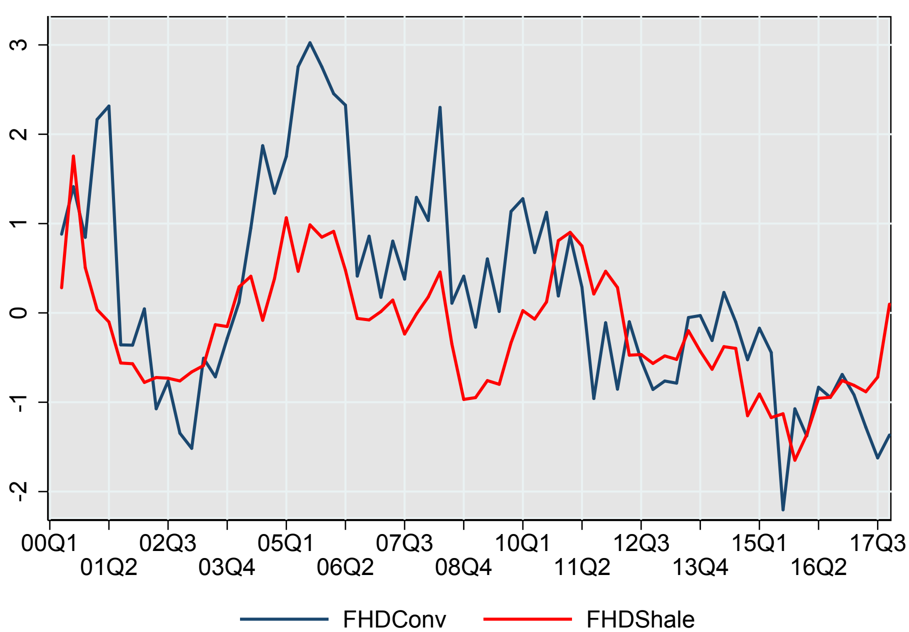
Figure 5.3 compares the time series of official shale oil production by the EIA with the one constructed by aggregating production from our identified shale producers, where production from each shale producer is weighted by the market share of shale oil production at each point in time. [16] The graph shows that, while our estimates only account for half of the total shale production, we are able to track very well the unconventional production dynamics during the shale revolution era.

The aforementioned firm classification allows to construct our specific indicators of default risk: a unique series FHD_t for the period 1983Q3-1999Q4 and two distinct series, $FHDConv_t$ and $FHDShale_t$ for conventional and shale producers respectively during 2000Q1-2017Q4. Figure 5.4 shows the unique pre-shale indicator (upper panel) and

[16]By weighting production of the identified shale producers we avoid overestimates of shale production in the first part of the sample, when conventional extraction was still made by companies experimenting new production technologies.



(a) Altman z-score 1983-1999



(b) Altman z-score 2000-2017

Figure 5.4: Standardized Altman z-score of US E&P companies (SIC code 1311); z-scores are preliminary winsorized within the interval 0-12 to exclude outliers. The upper graph plots the sample median Altman z-score from 1983Q2 to 1999Q4; the lower graph plots the sample median Altman z-scores from 2000Q1 to 2017Q4 differentiating between shale and conventional producers on the basis of the identification strategy described in this Section.

the two indicators for conventional and shale companies (lower panel), where small values indicate high default risk. The lower panel shows that the Altman z-scores have been trending down since the late 2000s for both types of producers, and these trends accelerated between 2013 and 2015, i.e. during the latest oil slump.

5.3 Financial speculators

To account for the presence of financial speculators interacting with oil producers, we include a measure of speculator risk aversion γ_s. We follow Etula (2013) and construct a measure of effective risk aversion based on broker-dealer and household balance sheet data from the US Flow of funds. This indicator is negatively correlated with speculators' capital constraints and previous contributions have shown its substantial effectiveness to predict commodity futures returns.[17]

In addition, we also include a measure of speculators' preference for investments in the commodity markets ($SPcc$) based directly on banks' regulatory reporting. This indicator is more closely related to the commodity market than the previous measure. We source the Federal Reserve banks' micro data from Compustat and construct our indicator as the ratio between the market value of banks' off-balance sheet commodity exposure and total trading assets.[18] In each quarter, the bank-level indicator of commodity preference is therefore as follows:

$$SPcc_t = \frac{\sum Commodity\ financial\ derivatives\ in\ the\ trading\ book_t}{Total\ trading\ assets_t} \tag{5.6}$$

where the numerator sums across financial derivatives whose underlying is either a single commodity or a commodity index that are valued in the trading book of the bank. In the following analysis we use an aggregate measure of commodity exposure corresponding to the sectoral median of $SPcc_t$ across reporting banks.

The two measures are displayed in Figure 5.5. The Broker-Dealer (BD) effective risk aver-

[17] The effective risk aversion measure is as follows

$$ERA_t = 1 + \frac{\text{Broker-dealer equity}_t}{\text{Household equity}_t}\left(1 - \frac{\text{Broker-dealer leverage}_t}{\text{Market leverage}_t}\right)$$

For details on how each term is constructed, see Etula (2013).

[18] Federal Reserve micro data provide information on the contract amount for all derivative contracts committing the reporting entity to purchase or sell commodities such as agricultural products (e.g., wheat, coffee), precious metals (e.g., gold, platinum), and non-ferrous metals (e.g., copper, zinc).

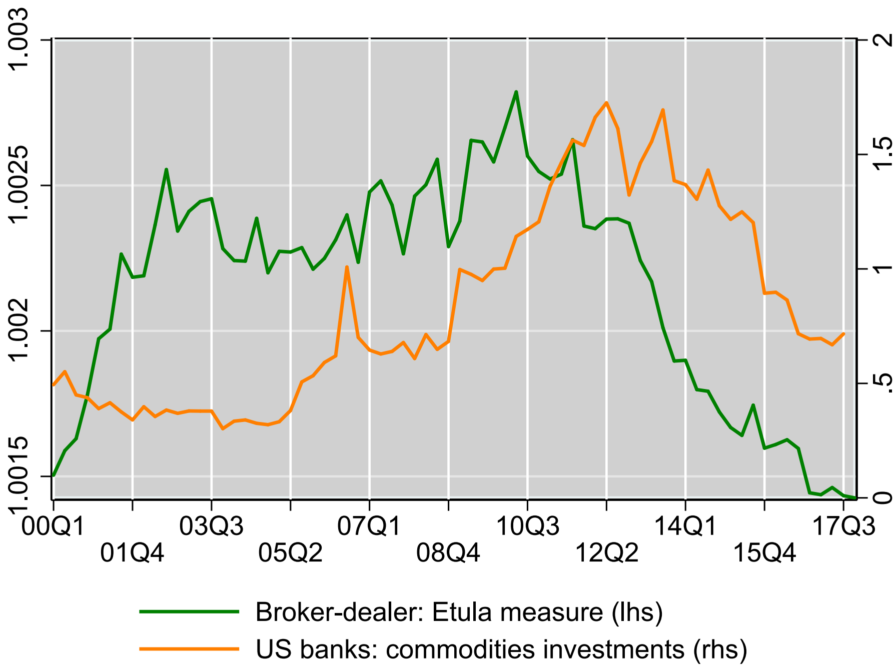


Figure 5.5: Two measures of broker-dealer exposure: the effective risk aversion (green line) and the median of the off-balance sheet exposure in commodity derivatives (yellow line). The green line represents the non detrended version of the risk aversion measure proposed in Etula (2013).

sion (green line) grew substantially in early 2000's and remained quite stable thereafter, indicating the ample liquidity of U.S. banks; since 2010, it progressively decreased as a consequence of stricter financial conditions with the global financial crisis. On the other hand, the exposure in commodity derivatives (yellow line) increased steadily since 2006 – the beginning of the financialization era – and peaked in 2012; in mid-2012, due also to stricter regulatory frameworks limiting the proprietary trading of derivatives by US banks, the commodity exposure started to decline, albeit remaining well above the pre-financialization levels.

5.4 Results

Empirical estimates for Equation 5.1, 5.2 and 5.3 are reported in Table 2. We empirically examine the drivers of the risk premium embedded in WTI futures contracts before and after the advent of shale oil. Equation 5.1 is estimated between 1983Q1 and 1999Q4 with results reported in the first column of Table 2 while equations 5.2 and 5.3 are estimated between 2000Q1 and 2017Q4 and the corresponding results are displayed in columns 2-5

	(1)	(2)	(3)	(4)	(5)
Altman score - pre 2000	-0.090**				
	(0.04)				
Altman score - shale		-0.114**	-0.117**	-0.092**	-0.093*
		(0.04)	(0.05)	(0.04)	(0.05)
Altman score - conventional		0.052	0.066	0.049	0.060
		(0.03)	(0.04)	(0.03)	(0.04)
BD risk aversion				-0.107	-0.101
				(0.12)	(0.13)
BD commodity exposure				-0.112*	-0.108*
				(0.06)	(0.06)
Kilian Index	0.056	0.009	-0.008	0.003	-0.012
	(0.06)	(0.03)	(0.03)	(0.02)	(0.03)
3m T-Bill	0.017	0.007	0.023	0.022	0.045
	(0.02)	(0.04)	(0.05)	(0.04)	(0.05)
Futures basis	-0.135	-0.025	-0.039*	-0.031*	-0.044**
	(0.11)	(0.02)	(0.02)	(0.02)	(0.02)
GDP forecast	-0.040	0.057	0.074	0.069	0.083*
	(0.06)	(0.04)	(0.05)	(0.04)	(0.04)
Inventories		-0.138***	-0.150**	-0.141***	-0.137**
		(0.05)	(0.06)	(0.05)	(0.06)
Credit lines - shale			-0.040**		-0.044**
			(0.02)		(0.02)
Credit lines - conventional			0.012		0.022
			(0.01)		(0.01)

Table 2: Results from the regressions of crude oil futures returns on fundamental hedging demand proxied by default risk measures and controls. In column 1 the time span is 1983Q1-1999Q4, in columns 2-5 it is 2000Q1-2017Q4. Altman scores account for producers' fundamental hedging demand as described in Section 5.2. BD effective risk aversion is the (non-detrended) measure introduced in Etula (2013), BD commodity exposure is US banks exposure in commodity derivatives. The controls in the regression include Kilian Index, risk-free rate, futures basis, GDP growth forecast, % of available credit lines/total liabilities, OECD oil inventories (these last two series are restricted to the second time span because of data availability). Inventories and the two BD measures are in first difference. Standard errors in parentheses are robust for heteroskedasticity and autocorrelation. * Denotes significance at the 10% level, ** denotes significance at the 5% level, and *** denotes significance at the 1% level.

of the same table. The first column shows that, in the pre-shale and pre-financialization period, the producer side of the oil market had a key role in the fluctuations of the futures risk premium, which was tightly linked to hedging decisions of oil companies. In line with the model predictions, a higher fundamental hedging demand (a lower default risk) leads to a widening of the risk premium.

During the 2000s, the interplay between an increasing speculative activity in oil market and the expanding demand for hedging by shale producers had a material effect on the risk premia. On the producer side, columns 2-5 show that, once separately identified, only the default risk of shale producers remains significant and exerts a negative pressure on futures risk premia. As predicted by the model, shale producers have on average higher hedging needs than conventionals, and their reliance on external debt determines higher pressure on financial derivatives. This result also emerges when we include, as an additional control, the degree of financial soundness in terms of credit lines available to the company to cover its liabilities (columns 3 and 5). On the other side of the market, the commodity exposure of speculators becomes relevant in our extended sample that includes years in which leverage and commodity exposure varied markedly. Note that, for a given level of financial constraint, the specific exposure of speculators in commodity markets, which may depend on the regulatory framework on derivatives as well as on investment preferences, is relevant to capture their overall effect on risk premia (columns 4 and 5). When speculators' risk capacity is low, additional investment in commodities produces a negative effect on futures risk premia, as arbitrageurs require a higher compensation to accomodate the hedging demand of oil producers.

All in all, the empirical evidence in Table 2 suggests that the hedging pressure from producers remains a relevant driver of the futures risk premia. However, despite the increasing pressure coming from the rise of shale producers, the risk premia were curbed by the offsetting buying pressure from financial intermediaries taking long positions in oil derivatives.[19]

6 Conclusions

The advent of shale oil in the United States induced a structural transformation in the oil market. We show, both theoretically and empirically, that this process has relevant consequences on oil prices. We construct a consumption-based model with shale producers who interact with financial speculators in the futures market. Compared to conventionals, shale producers have a more flexible technology, but higher risk aversion and additional costs due to their reliance on external finance. Our shale model helps to explain

[19] We find similar evidence of a compression in the risk premium using a model based estimate of the "ex-ante" risk premium from the term structure model of (Hamilton and Wu, 2014), which we update until the end of our sample. Results are available upon request.

the observed pattern of aggregate hedging by US firms in the last decade. A comparative simulation of the shale-speculator and conventional-pure speculator models reveals that, on average, an oil sector populated by shale producers demand a higher amount of financial hedging contracts, creating more pressure on the sell side of the derivatives markets and amplifying the arbitrage friction (so the futures risk premium). The empirical analysis also shows that, in the era of shale oil, the hedging pressure of shale producers can be more relevant than that of conventional producers in explaining the oil futures risk premium. However, despite the increasing pressure coming from the rise of shale producers the futures risk premia were curbed by an offsetting buying pressure from financial intermediaries taking long positions in oil derivatives. Both shale producers and speculators are tightly linked to fluctuations in the credit cycle: the investigation of their joint dynamics is left as avenue of future research.

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