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RISK PREMIUM IN THE ERA OF SHALE OIL

by Fabrizio Ferriani[*], Filippo Natoli[*], Giovanni Veronese[*] and Federica Zeni[†]

Abstract

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

JEL Classification: G00, G13, G32, Q43.
Keywords: shale oil, futures, risk premium, hedging, speculation, limits to arbitrage.

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[*] Bank of Italy, Directorate General for Economics, Statistics and Research.
[†] Bank of Italy, Directorate General for Economics, Statistics and Research; Imperial College London.

1 Introduction[1]

The advent of shale technology 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 oil production becoming the second largest world producer, mostly on account of the output from shale wells (Figure 1.1, left panel). Shale firms differ from conventional oil producers on both the technology and financing sides. Fracking and horizontal drilling allow producers to respond more quickly to higher oil demand; however, the adoption of the new technology has required a massive expansion in capital expenditure 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 oil prices and the economy, it mainly focuses on producers' technology disregarding the financing side, which can be even more important in oil pricing: indeed, small and indebted shale firms may have a higher desire of hedging their production against future price drops using financial contracts. If not fully accommodated by other investors in the market, such upward hedging pressure would then result in higher risk premiums paid by producers. However, the joint evidence on hedging and risk premiums during the shale boom period seems puzzling: on one side, newly collected data show that the share of hedged production in the US has risen steadily after the crisis but dramatically collapsed thereafter (Figure 1.2); on the other side, the risk premium on the WTI oil, which has increased during the shale boom while the Brent risk premium remained constant, continued to rise even when hedging pressure in the US almost vanished (Figure 1.3). While variations in the exposure of financial investors in US markets can be partly responsible of this behavior, the overall picture remains unclear.

In this paper we aim at reconciling the evidence on hedging and prices by considering both technology and financing characteristics of shale producers within a unified model. Our analysis is both theoretical and empirical. First, we model shale producers interacting with financial speculators in the oil futures market, building on Acharya et al. (2013) (ALR henceforth), and show that the peculiar characteristics of shale producers crucially alter the transmission of demand shocks to prices. Second, we empirically examine the drivers of the futures risk premium, i.e. the premium required by investors in oil futures, before

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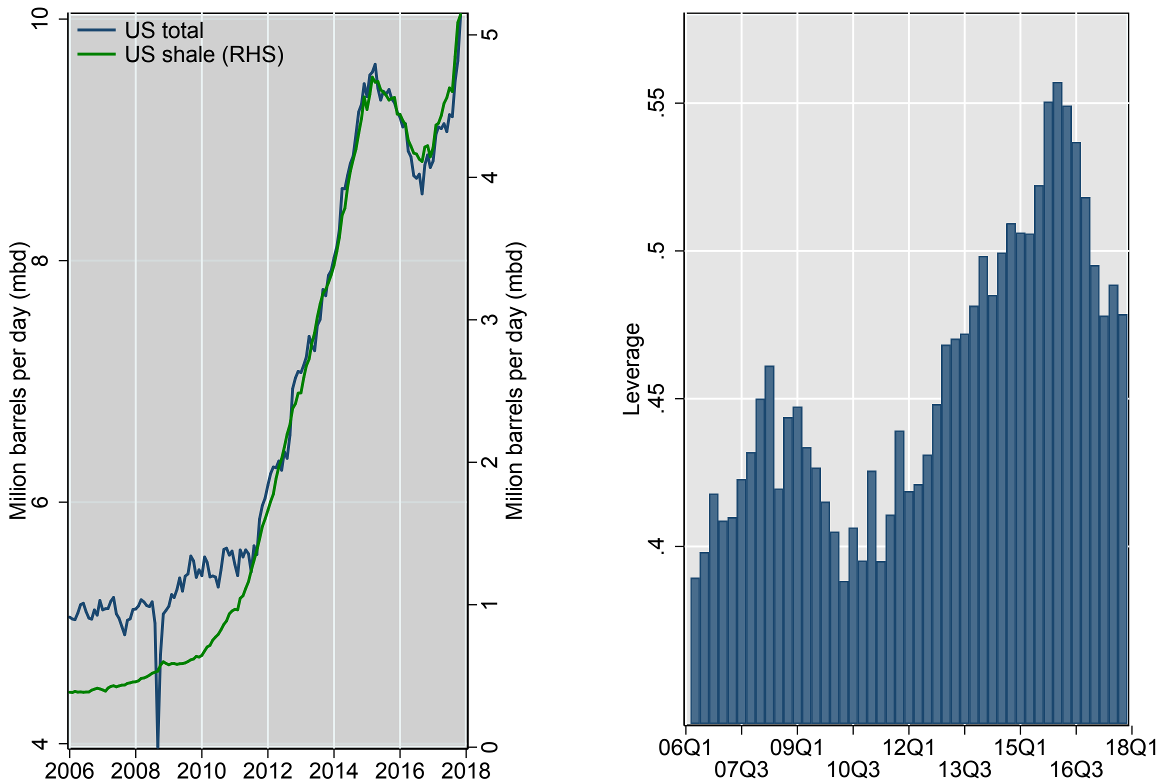


Figure 1.1: **Oil production and producers' leverage**. Left panel: US total vs. shale oil production, milion barrels per day (source: US Energy Information Administration). Right panel: median leverage (total liabilities/total assets) of the US oil sector (Exploration and Production companies with SIC code 1311).

and after the advent of shale oil: by identifying conventional and shale producers in the US oil industry, we show that in the shale era the upward pressure on the risk premium has increased, mostly on account of the activity of US shale producers.

Our producer-speculator model is designed as follows. The oil endowment in the economy is finite and agents live two periods. The producer is a shale firm which, with respect to a conventional one, has a more flexible supply schedule but higher risk aversion and non-negligible production costs, which he finances by a collateralized loan. He is risk averse, and hedges future profits by storing oil inventories and selling futures contracts. The speculator, who buys futures from the producer and lends money to him, is capital constrained and cannot satisfy his hedging demand fully (limits-to-arbitrage friction). With respect to a model in which the producer is conventional, the limits-to-arbitrage friction is amplified along two channels: (1) the higher risk aversion generates higher hedging pressure raising the futures risk premium, i.e. the premium required by the

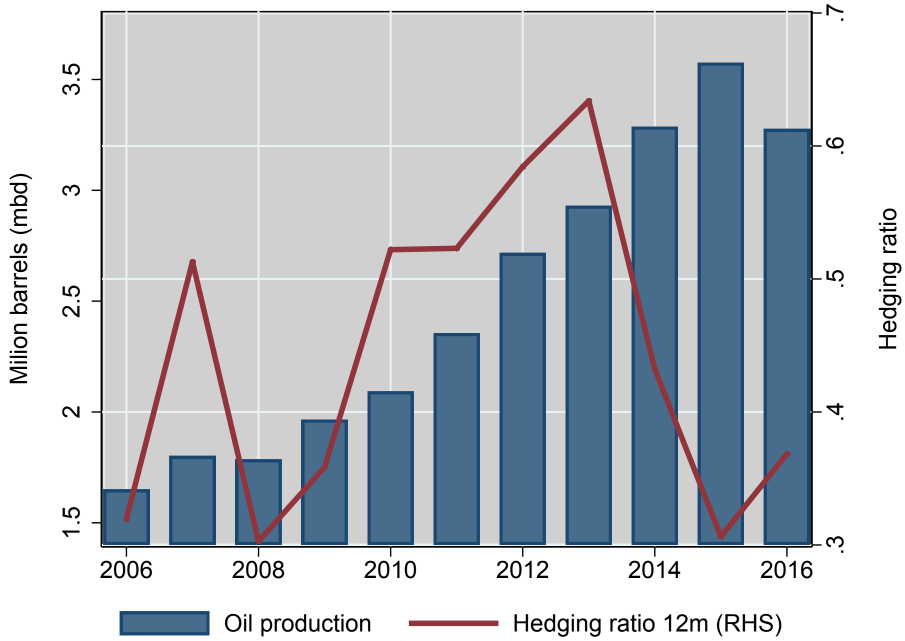


Figure 1.2: **Hedging ratio vs. production in the US oil sector**. For each company, the hedging ratio is the market value of all financial hedging contracts divided by 12-month ahead forecasted production (both hand-collected from 10-K filings, see Section 4). The sectoral hedging ratio is the average of the hedging ratios. Oil production is total production of US Exploration and Production companies in the sample.

speculator to accommodate the producer hedging demand (*risk aversion channel*), and (2) the more flexible supply schedule allows producers to sell more oil in the initial period in case of positive demand shocks: provided that supply is finite, this reduces the amount of oil to sale next period, lowering the number of barrels to be hedged but also raising the variance of (all possible) prices next period. This entails, in equilibrium, further upward pressure on the futures risk premium (*uncertainty channel*). A comparative simulation of the shale-speculator and conventional-speculator models shows that in the former the demand for financial hedging might be higher due to a higher producer's risk aversion, or lower due to the mechanics of collateral-based lending: lending requires oil barrels as collateral that, in bad states, are transferred from the producer to the creditor thereby reducing the quantity to be hedged by the producer (*collateral channel*).

Empirically, we test the predictions of the model on the WTI futures risk premium by regressing the latter on a measure of default risk of oil producers, controlling for the time-varying risk absorption capacity of speculators. On the producer side, we construct the default risk measure using firm-level balance sheet data; on the speculator side, we include the indicator of US broker-dealer risk aversion of Etula (2013) and construct a measure of commodity-related exposure using bank-level data. The sample is split in

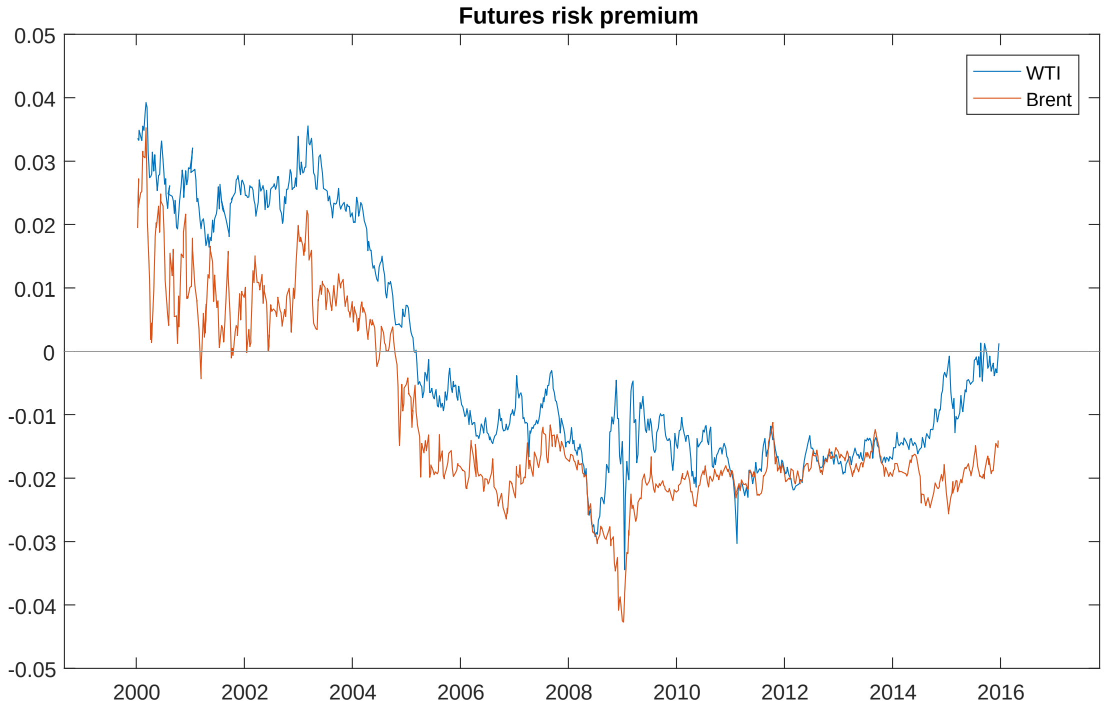


Figure 1.3: **Futures risk premium on WTI and Brent**. The two risk premiums have been estimated using the model of Hamilton and Wu (2014).

two subsamples (pre- and post-2000) to separate the pre- and post-shale era and the (almost concomitant) pre- and post- financialization of commodity markets.[2] In the pre-2000 sample, we regress the risk premium on a single default risk indicator (for the whole oil sector) without speculator controls; in the post-2000 sample, we include two separate measures of default risk for shale and conventional producers based on their production growth during the years of the shale boom, and control for the presence of speculators. Results show that, in the last two decades, the default risk of shale producers has become a more relevant driver of the futures risk premium than that of conventionals, reflecting the recomposition of the oil industry. Our result is complementary to those on the financialization of the oil market, which highlighted the role of speculators in driving pricing since the year 2000s. In this perspective, the shale revolution, which has peaked after the great financial crisis, has brought back producers at the heart of the price discovery mechanism.

[2]The U.S Energy Information Administration (EIA) started to record shale production in 2000; in the same years, financial institutions started to invest massively in commodity markets, the so called financialization of commodities.

This paper contributes to the literature in three ways. First, concerning pricing, it offers evidence in favor of the *normal backwardation theory*, which postulates that the risk premium is determined by the interaction between different types of investors, with respect to the *theory of storage*, which focuses on the role of the convenience yield of holding inventories.[3] Second, it accommodates two theories of optimal risk management predicting different hedging behavior of firms. On one side, Froot et al. (1993) state that firms funding their business through external finances hedge more (if those funds are more expensive than internal ones) to not miss profitable investment opportunities; on the other side, Rampini and Viswanathan (2010) and Rampini and Viswanathan (2013) predict that, if both borrowing and hedging are collateralized using current net worth, when the latter is low then financing needs predominate over hedging, so indebted firms hedge less to catch profitable investments. Using a hand-collected dataset on firms' hedging contracts, we calibrate our model and capture both the surge in aggregate hedging before 2013 due to the higher hedging pressure of shale firms (coherent with Froot et al., 1993) and the marked fall in 2014-15 following the oil price decline (reflecting the collateral effect described in Rampini and Viswanathan, 2010, Rampini and Viswanathan, 2013). Third, we give insights on the equilibrium implications of reserve-based lending, a lending practice in which the collateral (i.e., oil reserves) is the key asset of the firm to access external funds.

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

[3] The theory of normal backwardation has been pioneered by Keynes (1923) and generalized by Hirshleifer (1988, 1989, 1990); for the theory of storage, see Kaldor (1939), Working (1960) and Deaton and Laroque (1992).

overall US unconventional production – and show that firms using shale oil technology are more flexible in allocating output inter-temporally, thus suggesting a production pattern more consistent with Hotelling's theory of optimal extraction. Anderson et al. (2018) recast the traditional Hotelling 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 microfounded 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 (see Carter et al., 2017 for an up to date review on this topic). 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, Rampini and Viswanathan, 2013 for the theoretical framework and Rampini et al., 2014 and Rampini et al., 2018 for empirical applications). We capture this collateral constraint by modeling the common practice of reserve-based lending in the oil sector (see Azar, 2017 for details) and that of linking together producers' hedging and borrowing strategies (see Mello and Parsons, 2000).

3 Model

In this Section we describe our consumption-based model of crude oil, in which prices are determined in equilibrium from the interaction between an oil producer and a financial speculator. We first characterize all the agents in the economy; then, describe the optimization problem of producer and speculator and compute the equilibrium.

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 the risk-averse producer and the capital-constrained speculator gives rise to a limits-to-arbitrage friction that impacts equilibrium oil prices.

The model has two periods: $t = 0, 1$. The consumer has CES preferences over a consumption good (C) and oil (Q). The consumption good is supplied exogenously to the consumer and is lognormally distributed:

$$\Delta \log C_t = \mu + \sigma_c \eta_t \qquad \eta_t \sim \mathbf{N}(0,1)$$

where μ and σ_c are the drift and volatility of the process, respectively. In equilibrium, the 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 commodity supply, ω and ϵ are positive constants where the former identifies the share of oil consumption in the utility function and the latter the inter-temporal elasticity of substitution between C and Q.

In the following section we introduce two types of producers, a conventional and a shale producer, as well as a financial institution (speculator) that not only invests in the futures market (as in the ALR framework) but also provides credit to the producer. We first build our model, which features the shale producer interacting with the speculator; then, we compare our results with those obtained in the conventional producer-speculator economy outlined in ALR.[4]

3.1.1 Oil producer

The total oil endowment in the two periods is finite, and oil endowment in each period is denoted by g_0, g_1. The oil production firm is run by a risk-averse manager who aims at smoothing profits over time. At time 0, when aggregate demand shocks C_0 hit the economy, he stores optimally part of his endowment as inventories (i^*) and sells futures contracts (h^*) to hedge against low oil prices next period (S_1). A time 1, a new aggregate demand shock C_1 hits the economy: the manager sells the hedged part of his oil endowment at the futures price F_0, while the remainder at S_1.
The oil firm can be of two types: conventional (p) or shale (s).

3.1.1.1 Conventional producer The conventional firm has a predetermined production schedule which allows it to extract precisely g_t in each period. At time 0, it saves an

[4] For further details on the latter, see ALR.

amount $i_0^p \geq 0$, so oil supply to the consumer is

$$q_0^p = g_0 - i_0^p$$

$$q_1^p = g_1 + i_0^p$$

At the same time, it sells an amount of futures contracts h_0^p to hedge part of next period supply. Denoting the consumer's frictionless stochastic discount factor[5] 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[6]

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

with profit function

$$\pi_0^p = S_0(g_0 - i_0^p) \tag{3.1}$$
$$\pi_1^p = S_1(i_0^p + g_1) + h_0^p(F_0 - S_1) \tag{3.2}$$

and subject to the constraint

$$q_0^p \leq g_0 \Longleftrightarrow i_0^p \geq 0 \tag{3.3}$$

3.1.1.2 Shale producer The shale producer has different preferences, profits and technology. His salient characteristics are incorporated through three fundamental model assumptions laid out in the following paragraphs.

Flexible technology US shale producers have a flexible production technology, so they can quickly adjust production levels to accommodate temporary spikes in crude oil demand; they do so both by increasing the drilling activity in oil producing fields, as well as starting production in new fields (see, in this context, Bornstein et al. (2017)). To allow for a more flexible production schedule while keeping our finite oil supply setting we assume that, at time 0, the shale producer can increase supply by extracting a further

[5] The one prevailing under the assumption of no frictions.
[6] 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.

amount e_0^s from next period endowment. Oil supply at time 0 becomes

$$q_0^s = g_0 - i_0^s + e_0^s \tag{3.4}$$

where e_0^s can be positive in case of positive demand shocks.[7] When demand is high at time 0, the shale producer exploits such technology-embedded opportunity and supplies more than a conventional producer, whose technology does not allow to extract oil at the same time from g_1 reserves; conversely, at time 1, the shale producer has less barrels left to sale, so his supply is lower than that of a conventional producer. The higher flexibility in the time profile of oil supply for shale producers may alter the transmission of demand shocks to oil prices.

Reserve-based financing The shale technology has non-negligible (relatively to conventional oil) operational costs related to installation of facilities, drilling, and transportation equipment, that shale producers need to pay upfront. In the model, all these costs are summarized into a non-negative fixed cost

$$D_0$$

which is financed externally by the capital-constrained speculator. Consistent with a specific feature of debt financing in the shale oil sector, D_0 is collateralized on the value of current reserves, $S_0 g_0$.[8]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, i.e.

$$D_0 > S_0 g_0$$

the shale producer also incurs an extra payment in term of oil barrels *detracted* (by the speculator) from next period supply. Considering both the technology and external financing features, oil supply at time 1 becomes

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

[7]Obiously, inventories are accumulated in case of negative demand shocks, while additional barrels are supplied in case of positive shocks, so i_0^s and e_0^s cannot be both positive at the same time.

[8]The producer needs 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. The reserve-based lending scheme proposed in this model is a simplification of the existing reserve based lending agreements in place between shale producers and lenders, which also distinguish between producing and non producing reserves, as well as developed and undeveloped ones. For further details on reserve-based lending, see Azar (2017).

where $\psi \in [0,1]$ is the fraction of next period supply given to the speculator. In equilibrium, ψ is such that the expected loss for the latter (in terms of lower value of the collateral with respect to the credit granted) is fully offset[9], that is

$$\psi = \frac{[D_0 - \min(D_0, S_0 g_0)]}{E_0[\Lambda_1 S_1 g_1]} \tag{3.5}$$

where we impose that $D_0 < S_0 g_0 + E_0(\Lambda_1 S_1 g_1)$, i.e. shale producers' total profits are never fully absorbed by debt. Introducing reserve-base lending in the model makes both the producer's and speculator's appetite for futures contracts strongly related to the current level of spot prices. In other words, it creates a collateral channel which alters the amount of financial hedging made by the producer. The crucial assumption such that hedging and debt are contracted by the producer with the same counterparties finds empirical evidence from oil producers' 10-k reports.[10] Tables 1 and 2 summarize the behavior of the two types of producers at time 0 and 1.

	time 0	time 1
markets		
spot	sell $g_0 - i$ at S_0	sell $g_1 + i - h$ at S_1
futures	short on h futures	sell h at F_0

Table 1: Timeline of a conventional oil producer.

Managerial Risk-Aversion As to prefences, shale producers are modelled as more *risk averse* than conventionals. Specifically, we assume that

$$\gamma^s > \gamma^p \tag{3.6}$$

[9]Put differently, ψ verifies

$$\psi\, E_0(\Lambda_1 S_1 g_1) = D_0 - S_0 g_0 \qquad \text{when} \quad D_0 > S_0 g_0$$

[10] For example, a statement in the 2015 10-k report of Whiting Petroleum Corporation affirms that "*Counterparties to the Company's financial derivative contracts are high credit-quality financial institutions that are lenders under Whiting's credit agreement*"; similarly, in the 2013 10-k report of Carrizo Oil & 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*".

	time 0	time 1
	low demand	
markets		
spot	sell $g_0 - i$ at S_0	sell $g_1(1-\psi) + i - h$ at S_1
futures	short on h futures	sell h at F_0
credit	receive D	pay $S_0 g_0 (1+r)$
	high demand	
markets		
spot	sell $g_0 + e$ at S_0	sell $g_1(1-\psi) - e - h$ at S_1
futures	short on h futures	sell h at F_0
credit	receive D	pay $D(1+r)$

Table 2: Timeline of a shale oil producer.

In Appendix A, we make use of the extensive literature on corporate risk management, as well as of an empirical analysis on oil producers at firm-level, to motivate this modeling choice. In particular, we identify three key differences between shale and conventional producers concerning firm structure, manager compensation and financing, for which shale firms should have stronger incentives to hedge against oil price risk.

To sum up, by including the three aforementioned features, the problem of the shale producer reads as

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

where $x_0^s = i_0^s - e_0^s$ and

$$x_0^s \geq -g_1 \tag{3.7}$$

The profit function is

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

With respect to the conventional producer, the shale producer has a relaxed technology constraint, a state-contingent liability and a higher gamma.

3.1.1.3 Speculator. The financial institution (indexed by f) is a speculator in the oil futures market and creditor to the shale producer. It is ruled by a risk-neutral manager and subject to capital constraints that are proportional to the variance of time 1's profits.[11] At time 0, the financial institution lends D_0 to the shale producer and chooses the optimal number of long positions h^f in the crude oil futures market. The speculator's objective function 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

$$\pi_0^f = -D_0$$

[11] A capital constraint of this type is coherent with a value-at-risk limit. This formulation is taken from ALR, and is observationally equivalent to the case (that we do not consider in this setting) of a risk-averse manager with no capital constraints.

$$\pi_1^f = h_0^f(S_1 - F_0) + \min(D_0, S_0 g_0)(1+r) + \psi g_1(S_1)$$

A "pure speculator", which is modeled in ALR, shares the same characteristics of the financial institution described above; however, its business is limited to investing in commodity futures, with no lending activity. Hence, the profit function of a pure speculator reduces to $\pi_0^f = 0$ and $\pi_1^f = h_0^f(S_1 - F_0)$.

3.2 Optimization problem of the producer

We consider an economy composed by the consumer, the shale producer and the financial institution accommodating both producer's hedging and borrowing needs. From the shale producer problem, the FOCs with respect to x_0^s and h_0^s yield

$$\hat{x}_0^s = \frac{-S_0 + E_0(\Lambda_1 S_1) + \lambda^s}{\gamma^s \sigma^2} - g_1(1-\psi) + \hat{h}_0^s \tag{3.8}$$

and

$$\hat{h}_0^s = g_1(1-\psi) + \hat{x}_0^s - \frac{E_0[\Lambda_1(S_1 - F_0)]}{\gamma^s \sigma^2} \tag{3.9}$$

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

$$x_0^s \geq -g_1 \tag{3.10}$$

and σ^2 is the variance of the spot price.[12] 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 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

[12] 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

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

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^*.

(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. In line with a recent theoretical and empirical study in Rampini and Viswanathan (2010) on dynamic risk management in the airline industry, our model introduces a direct link between financing and risk management decisions of the firm, triggered by binding collateral constraints on the producers' reserves.

Combining (3.8) and (3.9) yields an expression for futures prices as a function of the spot price

$$F_0 = (S_0 - \lambda^s)(1 + r) \tag{3.11}$$

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 barrels at time 0, following the definition of the basis as in ALR.[13] In a model with a shale (instead of conventional) producer, 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 by the speculator

From the FOC of the financial institution one gets

$$\hat{h}_0^f = \frac{E_0[\Lambda_1(S_1 - F_0)]}{\gamma^f \sigma^2} - \psi g_1 \tag{3.12}$$

[13] 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 3.11, 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.

The tighter the capital constraint γ^f, the *lower* the number of futures contracts the speculator can afford to buy. 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

$$h_0^s = h_0^f \tag{3.13}$$

By recalling (3.9) and (3.12), 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. This because, by inheriting a portion of the shale producers' next period supply, speculators become naturally exposed to oil price risk. As a consequence, *producers' borrowing needs and the degree of collateralization have no role in shaping equilibrium prices*. The (expected) futures risk premium is

$$E_0\left[\frac{S_1 - F_0}{F_0}\right] = -(1+r)\mathrm{Corr}_0(\Lambda_1, S_1)Std_0(\Lambda_1)\frac{\sigma}{F_0} + \frac{\gamma^f\gamma^s}{\gamma^f+\gamma^s}(1+r)\sigma^2\frac{Q_1}{F_0} \tag{3.14}$$

with

$$F_0 = (S_0 - \lambda^s)(1+r) \tag{3.15}$$

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.

The equilibrium futures risk premium described above is higher with respect to that obtained in a conventional producer problem, mostly due to a higher limits-to-arbitrage component. This is because the three features which characterize the shale producer alter the transmission of aggregate demand shocks to prices along two channels:

- **Risk-aversion channel**: 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.

- **Uncertainty channel**: following a positive aggregate demand shock, 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 (across states) of spot and futures prices, which both negatively depend on the reduced, future oil supply. The increased quantity of risk prevails, entailing a *higher* futures risk premium.

Also, the model introduces an important **collateral channel**: lending requires oil barrels as collateral that, in bad states, are transferred from the producer to the creditor thereby reducing the quantity to be hedged by the producer. However, the lower demand for futures contracts by the producer is perfectly matched by an equivalent drop in speculators' appetite for them: the risk premium is *unchanged* at the conventional-pure speculator level.

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.[14]
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.

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 3: Parameter table.

[14]See also the online Appendix of ALR.

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). For each model, we compare producers' responses to large positive and large negative demand shocks, corresponding to the 75th and 25th percentiles of the distribution of log consumption growth, respectively.

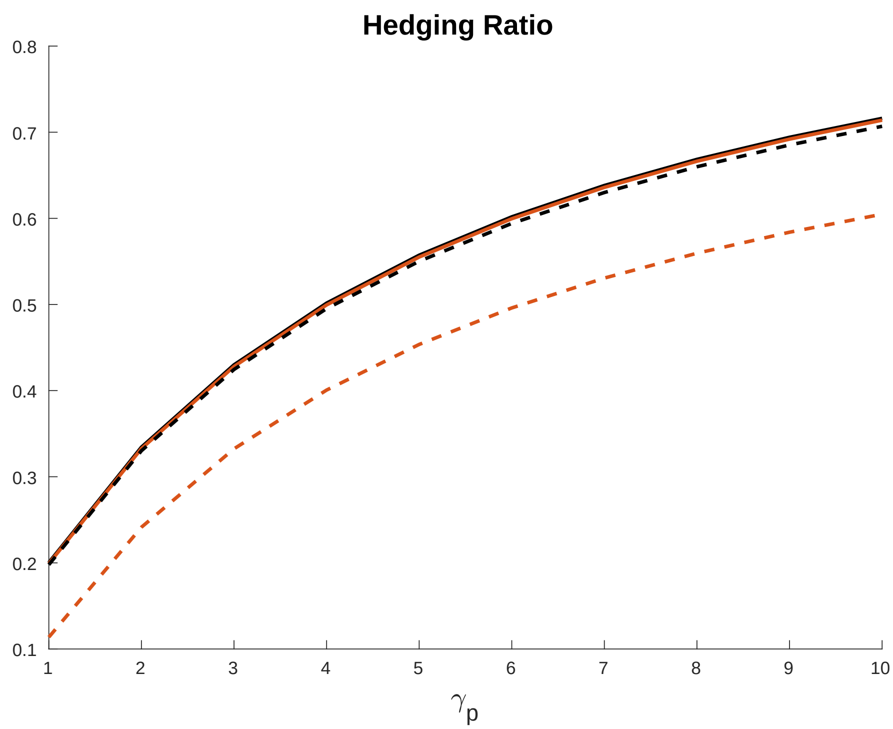


Figure 4.1: **Hedging ratio of shale vs. conventional producers**. Model-implied equilibrium hedging ratio as function of producer's risk aversion. Comparative statics for shale producers (red lines) and conventional producers (black lines) in case of positive shocks (solid lines) or negative shocks (dashed lines).

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 (the black and red solid lines are almost coincident), 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.

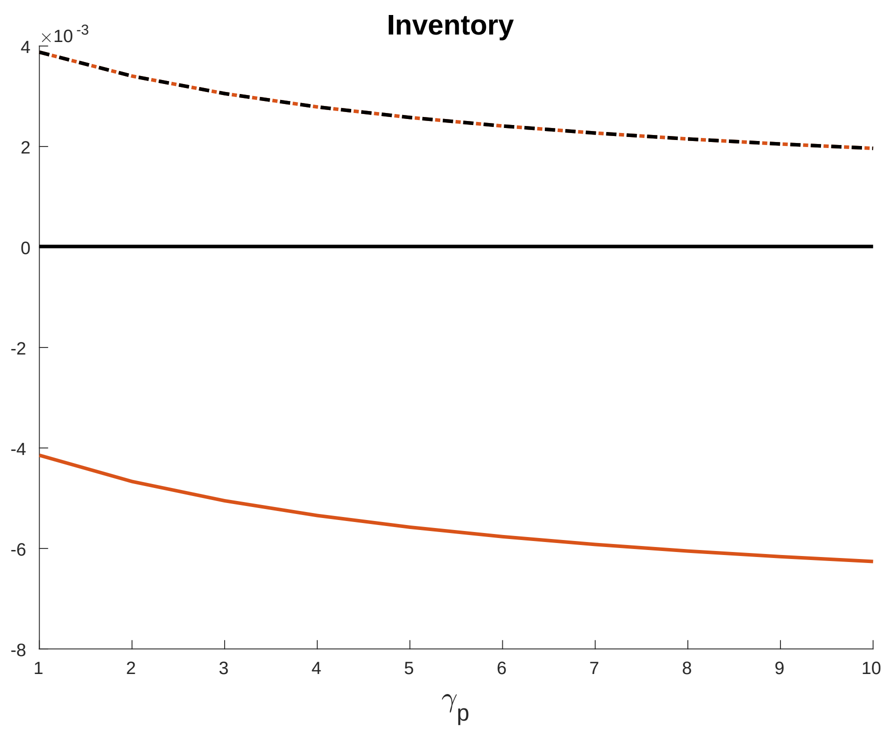


Figure 4.2: **Inventories of shale vs. conventional producers**. Model-implied equilibrium inventories as function of producer's risk aversion. Comparative statics for shale producers (red lines) and conventional producers (black lines) in case of positive shocks (solid lines) or negative shocks (dashed lines).

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.[15] 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[16] - thereby showing in the figure as *negative* inventories - while conventional producers face a binding stock-out constraint.

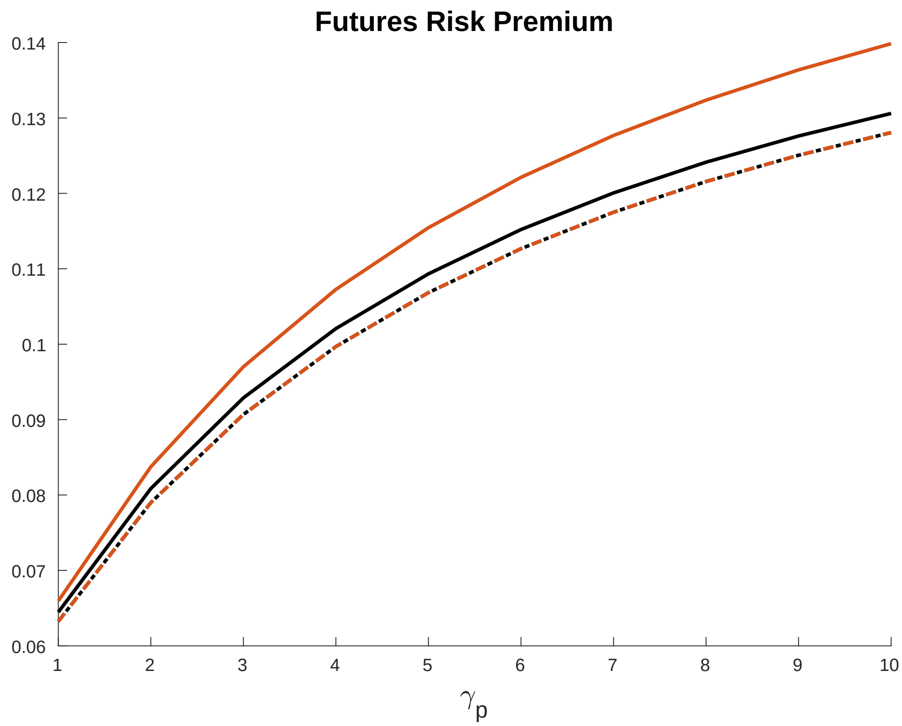


Figure 4.3: **Futures risk premium of shale vs. conventional producers**. Model-implied equilibrium futures risk premium as function of producer's risk aversion. Comparative statics for shale producers (red lines) and conventional producers (black lines) in case of positive shocks (solid lines) or negative shocks (dashed lines).

Figure 4.3 displays the equilibrium futures risk premium for conventional producers and shale producers. First of all, it is worth recalling 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.[17] 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 pro-

[15]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.

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

[17]Follows immediately from the specification in Equation B.1.

ducers can boost production at time 0, unlike conventional producers: as observed from 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.

To this end, we rely on a new hand-collected firm-level dataset providing detailed information on hedging contracts signed by "Exploration and Production" (E&P) companies between 2006 and 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.[18]

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

[18] 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).

by aggregating the value of all hedging contracts and summing across the whole sample of firms. Figure 1.2 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.

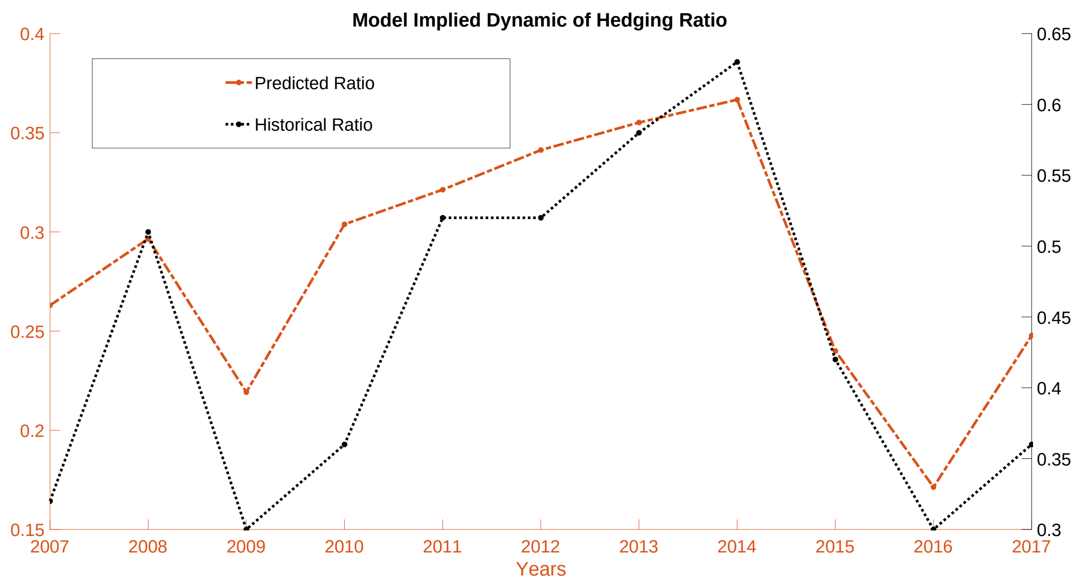


Figure 4.4: **Historical vs. model-based hedging ratio**. Historical hedging ratio: black line, right y-axis; model-based hedging ratio: red line, left y-axis.

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 4.4. The model makes a good job in matching the amount of hedging contracts in the period of the shale boom. By accommodating multiple theories of corporate risk management at once[19], it captures both the increase in hedging demand before 2013, as well as the fall thereafter. In particular, the model both predicts the increase in aggregate hedging pressure following the introduction of "fundamentally" more risk-adverse shale producers in the market[20], as well as the sharp drop in hedging pressure following the 2014 slump in crude oil prices, the latter being triggered by binding collateral constraints on the shale producers' reserves.

[19] We refer, in particular, to the study in Froot (1992) and Rampini and Viswanathan (2013) on the relationship between corporate risk management and financing needs.

[20] See the detailed discussion outlined in Appendix B. In modeling terms, the effect is given by an increasing risk-aversion parameter $\gamma^s = \gamma^p(1+\alpha)$, where α varies over time with the representative share of shale producers in the US oil market.

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 premiums. Our exercise starts from the model equilibrium condition presented in Equation B.1, and we estimate the following model as its empirical counterpart:

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

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 2000 shale producers – albeit at a slower pace – entered commodity markets. Therefore, to forecast risk premiums 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

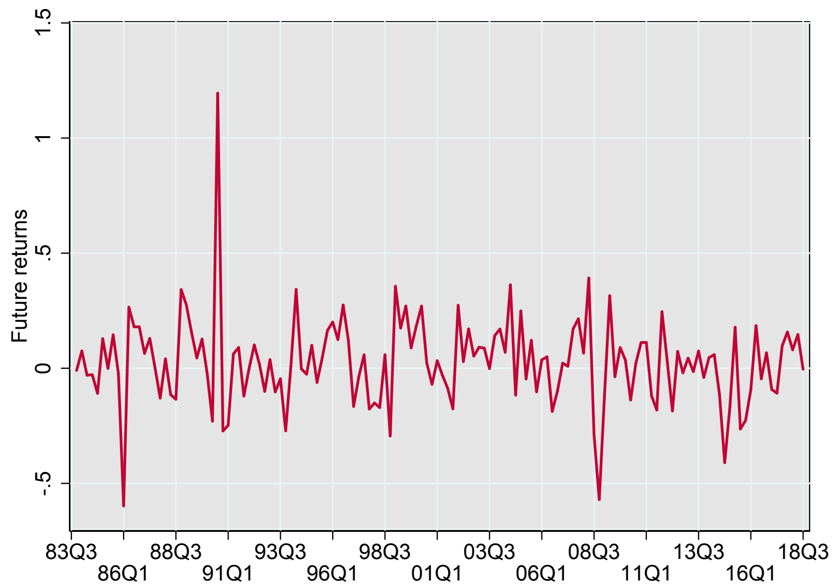


Figure 5.1: **Crude oil futures returns**. Returns are computed at quarterly frequency using prices of WTI Light Sweet Crude Oil quoted at NYMEX.

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 need to compute two distinct measures of $DefRisk$, distinguishing between shale and conventional producers. However, the identification of shale and conventional producers is an open question in the literature, because data detailing the type of crude oil production technology are not available at the firm level.

To address this issue we propose an identification strategy that exploits the dynamics of crude oil production in the US, as reported in Figure 1.1 (left panel). Since 2008-2009 total crude oil production has been trending up; the graph clearly shows how the increase was completely 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 2018Q2 was higher than the median of the entire US oil sector in the

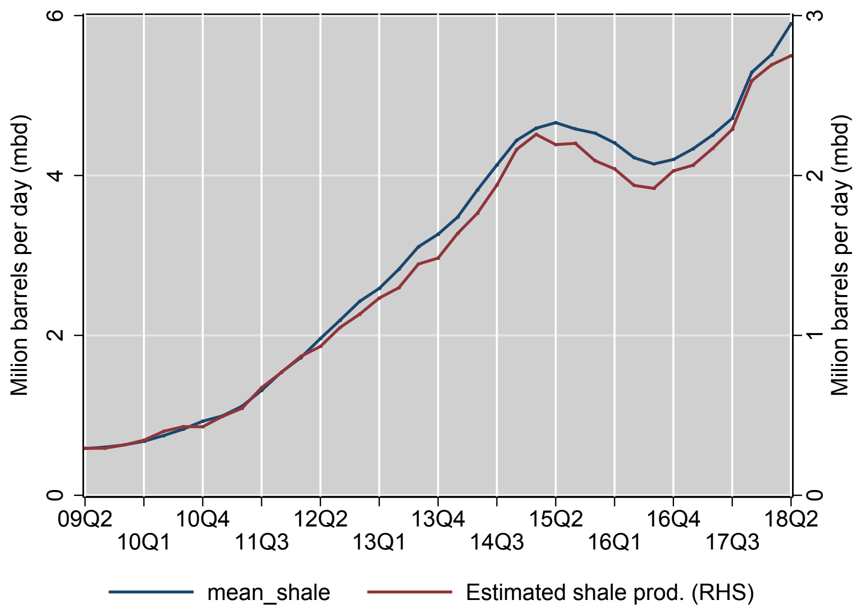


Figure 5.2: **Actual vs. estimated shale oil production**. Both series are measured in mbd; estimated production is scaled by the share of shale over total US oil production.

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 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 5.2 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.[21] The graph shows that, while our estimates only account

[21] 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

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 2000Q1-2018Q2. Figure 5.3 shows the unique pre-shale indicator (upper panel) and 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.[22]

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.[23] In each quarter, the bank-level indicator of commodity preference is therefore as follows:

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

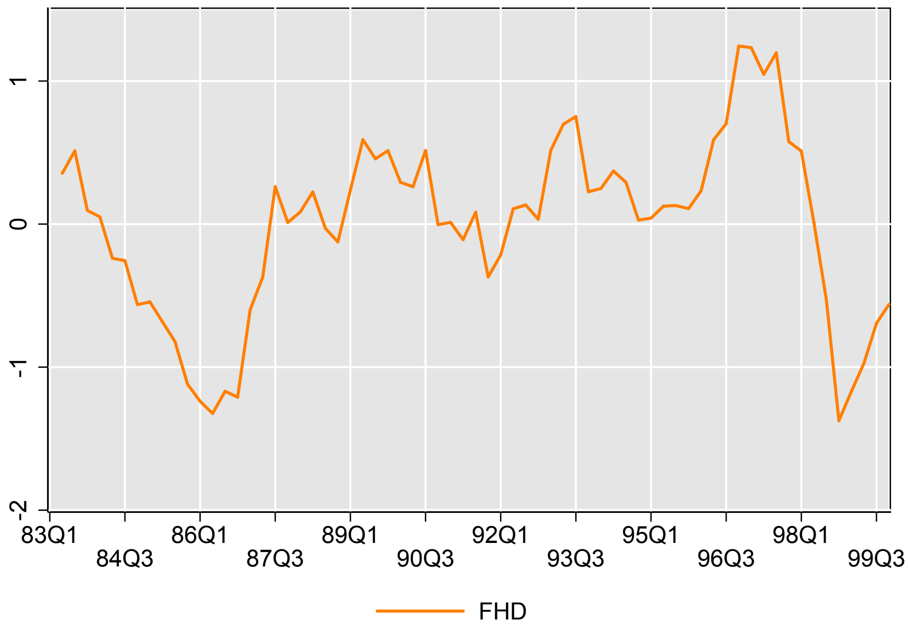
new production technologies.

[22] The effective risk aversion measure is as follows

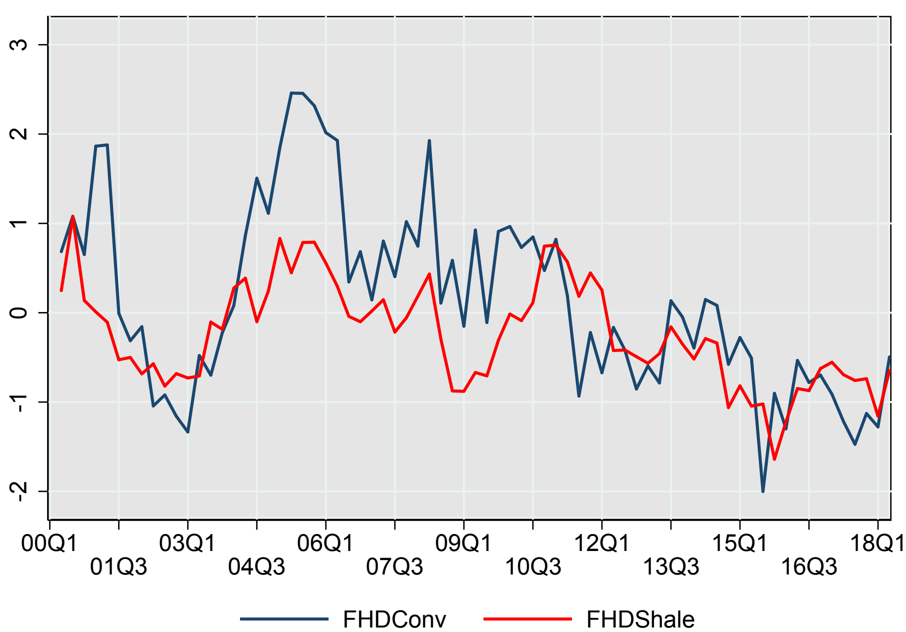
$$ERA_t = 1 + \frac{\text{Broker-dealer equity}_t}{\text{Household equity}_t}\left(1 - \frac{\text{Broker-dealer leverage}_t}{\text{Market leverage}_t}\right)$$

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

[23] 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).



(a) Altman z-score 1983-1999



(b) Altman z-score 2000-2018

Figure 5.3: **Altman z-score of the oil sector before and after the advent of shale**. Standardized median of the Altman z-scores of each US E&P companies. Firms' z-scores have been winsorized to exclude outliers.

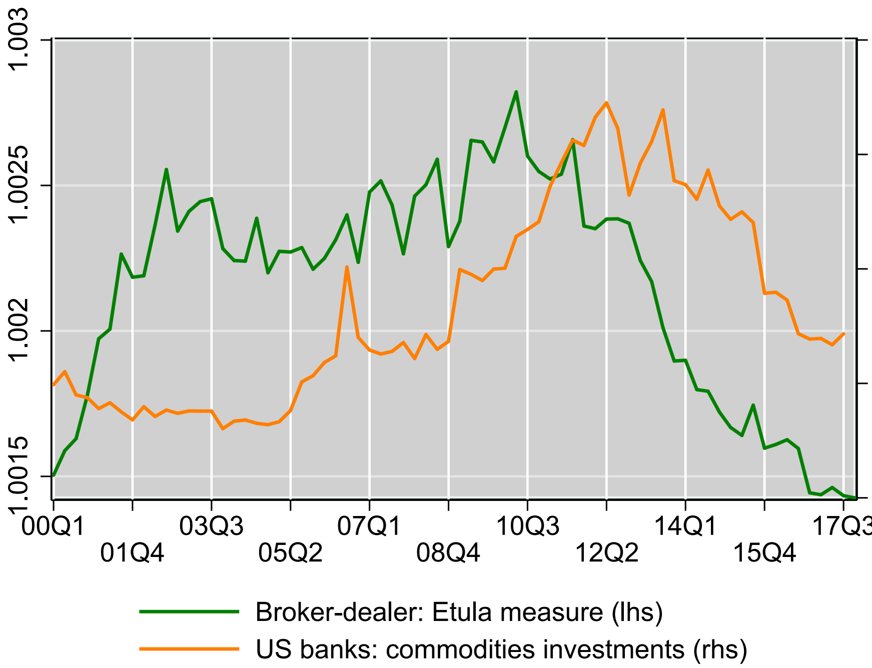


Figure 5.4: **Banks' risk aversion and commodity exposure**. The *effective risk aversion* measure (green line) proposed by Etula (2013) extended to 2017 (here not detrended). The commodity exposure (orange line) is the median of each US bank's off-balance sheet exposure in commodity derivatives.

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 5.4. The Broker-Dealer (BD) effective risk aversion (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 (orange 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

	(1)	(2)	(3)	(4)	(5)
Altman score - pre 2000	-0.154**				
	(0.06)				
Altman score - shale		-0.152***	-0.179***	-0.180***	-0.184***
		(0.05)	(0.06)	(0.06)	(0.06)
Altman score - conventional		0.054	0.074	0.067	0.078
		(0.04)	(0.05)	(0.04)	(0.05)
BD risk aversion				-0.080	-0.018
				(0.13)	(0.15)
BD commodity exposure				-0.017***	-0.008
				(0.01)	(0.01)
Kilian Index	0.049	0.034	0.026	0.036	0.026
	(0.11)	(0.02)	(0.03)	(0.02)	(0.03)
3m T-Bill	0.047	0.011	0.038	0.015	0.033
	(0.03)	(0.04)	(0.05)	(0.04)	(0.06)
Futures basis	-0.148	-0.028	-0.040*	-0.030	-0.040*
	(0.18)	(0.02)	(0.02)	(0.02)	(0.02)
GDP forecast	0.011	0.080*	0.100**	0.085*	0.100**
	(0.10)	(0.05)	(0.05)	(0.05)	(0.05)
SP&500-WTI correlation	0.076	0.057*	0.076**	0.068*	0.077*
	(0.07)	(0.03)	(0.04)	(0.04)	(0.04)
Inventories		-0.127**	-0.147**	-0.138***	-0.148**
		(0.05)	(0.06)	(0.05)	(0.06)
Credit lines - shale			-0.028**		-0.028*
			(0.01)		(0.02)
Credit lines - conv.			-0.012		-0.006
			(0.01)		(0.02)

Table 4: 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 2000Q1-2018Q2. 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, S&P500-WTI price 6M rolling correlation, % 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.

Empirical estimates for Equation 5.1, 5.2 and 5.3 are reported in Table 4. 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 4 while equations 5.2 and 5.3 are estimated between 2000Q1 and 2018Q2 and the corresponding results are displayed in columns 2-5 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 higher 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 premiums. 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 premiums. 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 premiums (columns 4 and 5).

All in all, the empirical evidence in Table 4 suggests that the hedging pressure from producers remains a relevant driver of the futures risk premiums. However, despite the increasing pressure coming from the rise of shale producers, the risk premiums are curbed by the offsetting buying pressure from financial intermediaries taking long positions in oil derivatives.[24]

[24]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.

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 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 demands a higher amount of financial hedging contracts, creating more pressure on the sell side of the derivatives markets and amplifying the arbitrage friction (and thus also 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. Our paper offers evidence in favor of the normal backwardation theory, which postulates the importance of financial trading in affecting prices through the futures risk premium; moreover, it reconciles two theories of optimal risk management predicting different hedging behavior of firms. 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.

Appendices

Appendix A

In our theoretical framework shale oil producers are designed as more risk averse with respect to conventional oil producers, which in turn generates a higher hedging pressure and, for a given capital constraint of speculators, raises the equilibrium futures risk-premium. To support our modeling assumption, in this section we present some empirical evidence in favor of the higher risk aversion of shale oil producers. In principle, if we limit the analysis to commodity risk management both categories of producers should exhibit a similar hedging demand, being exposed to the same risk factor, the oil price. However, this exercise would be quite reductive as it disregards the different operational structure of shale and conventional producers; moreover, it would confine the rationale for hedging to a single specific motivation, while the literature has established several factors behind firms' risk management decisions.

A first evidence of shale firms' higher risk aversion concerns their business model that is traditionally specialized in exploration and production (E&P) activities, and does not extend to the downstream services, such as refining. On the contrary, conventional producers are generally large vertically integrated companies that encompass both upstream and downstream activities so that their company-wide cash flows are less sensitive to oil price fluctuations, see Kumar and Rabinovitch (2013) and Boyer and Filion (2007). Moreover, and probably more interestingly, vertical integration could represent a substitute for risk management strategies as discussed in Mackay and Moeller (2007) who study the relation between risk management and firm value in the oil sector and find that vertically integrated and diversified firms generally display lower hedging ratios as they benefit from natural hedges.

Additional empirical underpinning to the higher risk aversion of shale firms emerges from the literature analyzing the interplay between managerial stock ownership and corporate risk management, see for example Smith and Stulz (1985) and Tufano (1996) for two seminal contributions. To understand this point, let's first consider that managers with insufficient wealth diversification are more likely to hedge in order to reduce fluctuations of their expected utility. Under this assumption, the manager's decision to engage in risk management either on his own or through the firm itself essentially depends on cost motivations. The theoretical model in Smith and Stulz (1985) predicts that managers owning a significant portion of the firm are more likely to hedge to compensate the poor

	Mean	p25	p50	p75
Small producers				
% stock compens. (board directors)	0.33	0.04	0.34	0.54
% stock compens. (CEO)	0.34	0.00	0.34	0.57
Major companies				
% stock compens. (board directors)	0.18	0.00	0.00	0.36
% stock compens. (CEO)	0.17	0.00	0.00	0.31

Table 5: **Share of stock ownership over total compensation for board directors and CEOs**. Small producers include firms as described in Section 4, major companies include Chevron, Exxon, Total, Repsol, Petrobras, BP, Statoil, Royal Dutch Shell, and Eni. Annual data from Bloomberg in the period 2004-2016.

diversification of their portfolios. To test this hypothesis we collect data on stock compensation from Bloomberg for the sample of E&P firms described in Section 4 and for some major oil corporations. Table 5 reports descriptive statistics on the share of stock ownership over total annual compensation for board directors as well as for the company's CEO. The likelihood of risk management activities driven by portfolio diversification intents seems particularly relevant for small independent E&P companies that exhibit a significantly higher fraction of stock ownership in the hands of executive directors.

Finally, we investigate the degree of managerial risk aversion of oil producers also with respect to their reliance on external financing. Froot et al. (1993) introduce a theoretical framework to motivate risk management as a result of costly external financing. If a firm does not hedge, it may be exposed to some variability in its cash flows and ultimately in the amount of funds that are necessary to finance new investments.

	Mean	p25	p50	p75
KZ index - small producers	0.87	0.10	1.00	1.78
KZ index - major companies	-1.06	-1.06	-0.36	0.28

Table 6: **Kaplan and Zingales (1997) index**. The index is computed for all E&P companies with SIC code 1311 available in Compustat, and for major companies Chevron, Exxon, Total, Repsol, Petrobras, BP, Statoil, Royal Dutch Shell, and Eni. Quarterly data in the period 2000-2018. The Kaplan and Zingales (1997) index is computed according to the version discussed in Lamont et al. (2001).

This outcome is clearly undesirable and could be mitigated by external financing, but only up to some extent if *"the marginal cost of funds goes up with the amount raised externally"*, for instance because of informational asymmetries or bankruptcy costs. On the contrary, by hedging, firms ensure they have sufficient internally generated funds when attractive investment opportunities arise so as to temper underinvestment. To test the relevance of external financing for managerial risk aversion we adopt the index introduced by Kaplan and Zingales (1997) which is based on five accounting ratios; higher values of the index are associated with more binding financial constraints. According to evidence provided in Table 6 the reliance on external financing is more compelling for smaller independent E&P companies that also frequently face a more limited access to financial markets to raise capital.

Appendix B

We provide a sketch proof to show that, for any value of the demand shock $C_0 \in [\underline{C}, \overline{C}]$, our shale producer-speculator variant of the ALR model yields a limits-to-arbitrage friction

$$\mathbb{E}[\Lambda(S_1 - F_0)] = \frac{\gamma^f \gamma}{\gamma^f + \gamma} q_1 \sigma_S^2 \tag{B.1}$$

which is *at least as severe* as the one implied by the baseline ALR model. We avoid indeterminate solutions by excluding extremely high shocks $\overline{C}$ above which the shale producer is willing to extract all of its next period supply at time 0, as well as extremely low shocks $\underline{C}$ below which the shale producer is forced to give up all of its next period supply (to the speculator) at time 0. That is, we analyze the cases in which

a. $\bar{c} < C_0 < \overline{C}$:

$$\{x_0^s \in (-g_1, 0), \psi = 0\}$$

b. $\underline{c} < C_0 < \bar{c}$:

$$\{x_0^s \in (0, g_0), \psi = 0\}$$

c. $\underline{C} < C_0 < \underline{c}$:

$$\{x_0^s \in (0, g_0), \psi \in (0, 1)\}$$

Case a). Recalling the expression (3.4) for the shale producer's output in period 1, we have that

$$q_1^s = g_1 + x_0^s < g_1 = q_1^p \tag{B.2}$$

A reduced output in the next period q_1^s reduces the quantity to be hedged by the shale producer h_0^s, which in turn reduces the limit-to-arbitrage friction (B.1) in equilibrium. However, it also makes spot prices more sensitive to unexpected demand shocks in the next period, i.e. it increases the spot variance in (B.1) as

$$\sigma_S^2 = k(q_1^s)^{-2/\epsilon} > k(q_1^p)^{-2/\epsilon} \tag{B.3}$$

Provided $\epsilon < 2$ (which is indeed the case in our calibration), this term predominates and the limits-to-arbitrage friction is *higher* in the shale producer-speculator model then the ALR model.

Case b). This case is trivial as the shale producer's profit function differs from the one in ALR only for a constant term $-D_0(1 + r)$ (debt repayment to the speculator). First order conditions with respect to the choice variables x_0^s, h_0^s are not affected by the shale producer's features and yield the same equilibrium limits-to-arbitrage friction as the baseline ALR model.

Case c). When the collateral constraint ψ is binding, the producer's output in period 1 reads

$$q_1^s = g_1(1-\psi) + x_0^s \tag{B.4}$$

the remainder of the shale producer's supply ψg_1 is transferred to the speculator at time 0, which in turn sells it to the market at time 1. Such physical transfer lowers *equally* the optimal hedging ratio h_0^s in (3.9) as well as the speculative ratio h_0^f in (3.12): the collateral constraint ψ cancels out from the market clearing condition (3.13), yielding the same limits-to-arbitrage friction as in (B.1). Accounting for both the shale producer and the speculator shares of supply, total output in the next period reads

$$q_1^s + \psi g_1 = g_1 + x_0^s \tag{B.5}$$

It is simple to show that the optimal inventory choice x_0^s in (3.8) solves the same first order condition as the one in the ALR model (the counteractive effects of a reduced supply next period and a reduced quantity be hedged cancel out). Again, the limits-to arbitrage friction takes the same value as the baseline case with conventional producer.

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