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U.S. SHALE PRODUCERS: A CASE OF DYNAMIC RISK MANAGEMENT?

by Fabrizio Ferriani[*] and Giovanni Veronese[*]

Abstract

Using more than a decade of firm-level data on U.S. oil producers' hedging portfolios, we document for the first time a strong positive link between net worth and hedging in the oil production sector. We exploit, as quasi-natural experiments, two similarly dramatic oil price slumps, in 2008 and in 2014-2015, and we show how a shock to net worth affects risk management practices among E&P firms differently depending on their initial financial positions. The link between net worth and hedging decisions holds in both episodes, but in the second oil slump we also find that leverage and credit constraints play a significant role in reducing hedging activity, a result that we attribute to the marked increase in leverage following the diffusion of shale technology. Finally, we test if collateral constraints also impinge the extensive margin of risk management. Though in this case the effect is less apparent, our results generally point to a more limited use of linear derivative contracts when a firm's net worth increases.

JEL Classification: D22, G00, G32.
Keywords: dynamic risk management, hedging, derivatives, shale revolution, oil price collapse.

Contents

[*] Bank of Italy, Directorate General for Economics, Statistics and Research.

Hedging transactions expose us to risk of financial loss in some circumstances [...] Additionally, hedging transactions may expose us to cash margin requirements.
Whiting 10-K

1 Introduction[1]

Understanding corporate hedging strategies remains a fundamental challenge in modern corporate finance. Theoretical and empirical contributions have focused on the motivations and determinants of firms optimal hedging policies as well as on the effects of the hedging practices on firm value. However, firms' financial and operating policies are typically drawn jointly, so that establishing the causal effects of hedging or explaining hedging behavior can be a difficult task, hindered by endogeneity and reverse causality issues.

In this paper we investigate the hedging practices of U.S. companies in the oil exploration and production (E&P) sector. This setting is particularly amenable to analyze corporate behavior, as firms are exposed to a common risk factor (the oil price) and have access to a wide range of hedging instruments (Haushalter 2000; Haushalter et al. 2002; Jin and Jorion 2006). Oil producers hedge their production for a number of reasons including, but not limited to, commodity price risk management, lock in of cash flows to fund future investments, and loan covenants requiring minimum hedging amount. Haushalter (2000) offers a seminal contribution documenting substantial heterogeneity in hedging strategies in the E&P sector.

Our analysis covers the decade following the adoption of shale technologies. In this period the surge in production was phenomenal: U.S. crude oil production almost doubled from around 5 million barrels per day (mbd) in 2006 up to about 10.5 mbd in early 2018 (see Figure 1). The progress in hydraulic fracturing techniques has sustained increasing gains in the productivity and cost efficiency of E&P firms whose functioning has become more akin to a Hotelling producer. This evidence is presented in Bjørnland et al. (2017) where North Dakota firms using shale oil technology are found to be more flexible in allocating output intertemporally. Greater drilling responsiveness to oil prices is also documented in Newell and Prest (2017) and Anderson et al. (2018) who find from well-level data from Texas

[1]The views expressed in this paper are those of the authors and do not necessarily reflect those of the Bank of Italy or the Eurosystem. The authors wish to thank Pietro Catte, Paolo Conteduca, Florian Heider, Taneli Mäkinen, Francesco Manaresi, Alfonso Rosolia, Enrico Sette, and seminar participants at Bank of Italy and NCB4 meeting for useful comments and suggestions on a previous version of this paper. All remaining errors are our own.

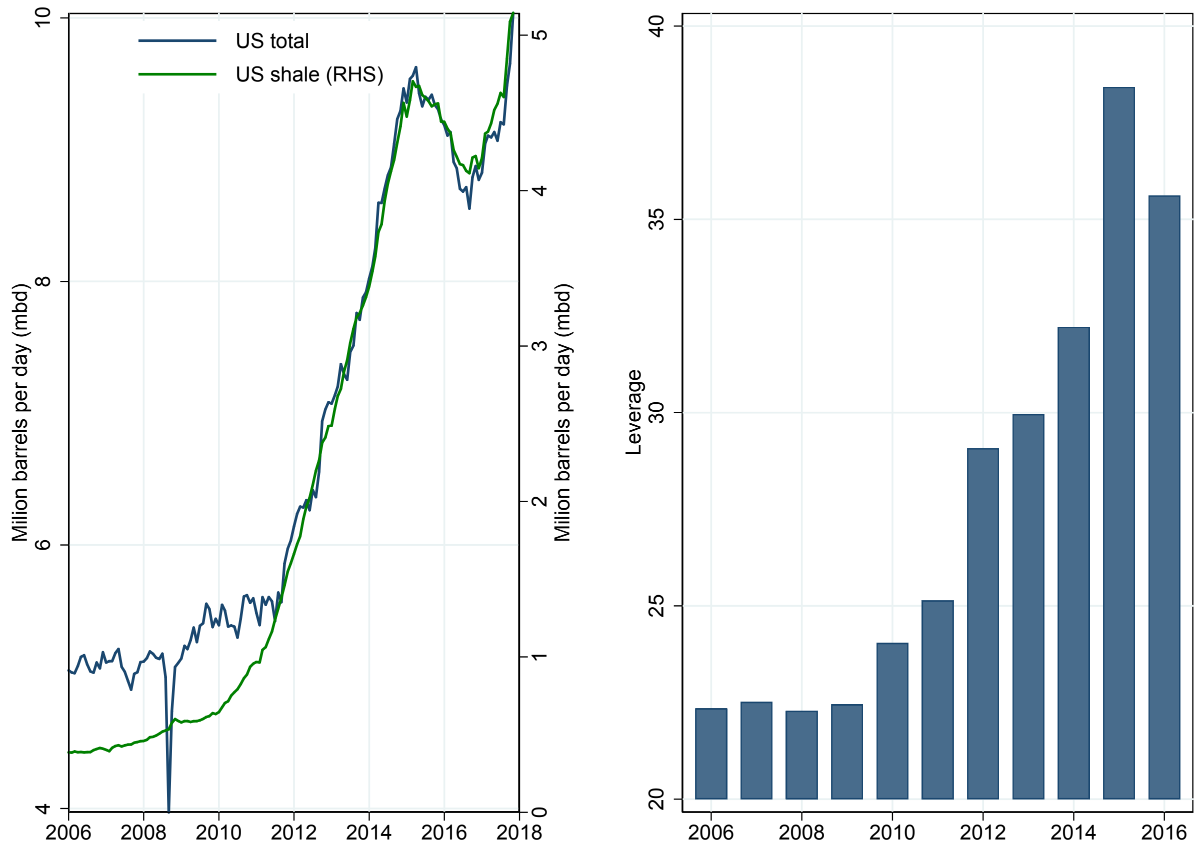

Figure 1
US oil production and leverage
The left plot displays the total US crude oil production and shale oil production measured in terms of million barrels per day (mbd); both series are from EIA. Shale-oil production includes hydraulically fractured production originated from EIA plays: Monterey, 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 Debt/Assets for selected US E&P companies. Data are from Bloomberg, details on the firms included in the sample are available in Section 3.

that the drilling pattern, rather than oil production, is consistent with Hotelling's theory. By altering their supply response to forward prices at different horizons, the advent of the shale revolution may have translated also into changes in hedging strategies of oil companies (Domanski et al., 2015, Ferriani et al., 2018).

To finance the adoption of these new technologies oil producers have levered up substantially. As shown in the right plot of Figure 1, E&P firms accumulated debt to finance their operational growth in the most recent years; this resulted in a rapid increase of the U.S. oil and gas producing sector indebtedness, on the back of optimistic expectations regarding oil price developments (Domanski et al., 2015). This expansion occurred in a period of historically low interest rates with fairly stable oil prices (Azar, 2017). However, the buildup in leverage was not inconsequential for producers. According to Gilje et al. (2017) it materially affected firms' output and investment decisions and may have ultimately made the oil market more exposed to financial shocks (Dale, 2015).

Specifically, we explore how risk management by oil producers relates to increasing default risk and more tightening financial constraints. In the original literature pioneered by Froot et al. (1993) firms engage in hedging as a result of costly external financing; by hedging firms may limit the variability of internally generated cash flows and ultimately the amount of funds that are necessary to finance new investments. However, this theoretical prediction has been challenged by modern theories of dynamic risk management, claiming that limited or incomplete hedging characterize optimal risk management strategies for financially constrained firms (see Holmström and Tirole, 2000, Mello and Parsons, 2000). More recently Rampini and Viswanathan (2010) and Rampini and Viswanathan (2013) model the dynamic interplay between standard financing and risk management with collateral constraints. Their theoretical framework has been validated in recent studies documenting how financial constraints do actually limit firms' risk management (Rampini et al., 2014, Rampini et al., 2017).

We are the first to provide evidence of the important role of collateral in hedging decision in the oil producing sector, filling a gap in the literature on risk management Carter et al. (2017). Our empirical investigation relies on a new firm-level dataset of over 100 E&P U.S. oil producers, between 2006 and 2016. We hand-collected data from the companies' annual reports (10-k) on the notional amount of each hedging contract as well as on the different types of financial contracts used to hedge the oil annual production. With respect to other empirical studies investigating corporate risk management, our detailed dataset allows us to construct a more precise measure of the intensive margin of firms' hedging rather than a simply indicator signaling the use of derivative contracts (Guay and Kothari, 2003). In addition, thanks to the panel structure of our data, we are able to study the link between risk management and financial constraints not only by focusing on cross-sectional evidence but also exploiting sizable within-firm variation, a feature that we consider essential to study hedging dynamics in a sample of firms experiencing deep financial and technological changes. Finally, the additional information on derivative categories represents an imperative condition to extend the analysis to the optimal hedging strategies, an issue frequently disregarded in the literature because of data limitations (see Adam, 2009 or Mnasri et al., 2017b for some few exceptions).

The particular environment examined enables us to make progress on several dimensions, which are central to the literature on financial risk management. First of all, we focus on oil producers as in this context the functioning of the collateral channel is likely to be even more central in explaining risk management practices. Indeed, revenues for pure oil producer are more sensitive to oil price fluctuations compared to large and vertically integrated companies encompassing both upstream and downstream activities (Boyer and Filion, 2007 and Kumar and Rabinovitch, 2013). Moreover, the dynamic trade-off between firms' financing and risk management under collateral constraints is even amplified in this case as collateral pledged by oil producers takes the form of oil reserves, valued at market prices (see Office of the Comptroller of the Currency, 2018). We empirically document a strong positive link between net worth, representing our measure of financial constraints, and hedging in the oil producing sector. Our findings are robust to several checks. First, we consider different definition of net-worth, based on accounting as well as market based indicators to ensure that our results do not depend on a particular measure. Second, we do not limit to cross-sectional evidence but also look at the mere time-series dimension and test the impact on hedging by using net worth dynamics and a longitudinal setting. Third, we restrict the analysis to specific subsamples both time and firm-wide to account for periods of price declines and firms' defaults. Even more interesting, our results are confirmed also in an instrumental variable setting that we adopt to cope with possible endogeneity issues. We base our identification strategy on two different indicators: a measure of oil reserve revisions driven by exogenous price variation and an indicator of operational efficiency defined at well level. In both cases we find strong support for a positive causal link between a firm's net worth and its hedging ratio.

As a second contribution, we study how extreme market conditions in the oil market, leading to tighter financial conditions, influenced risk management in the US E&P sector. In the aggregate, hedging by oil producers recorded a sizable reduction following the two oil price collapses in 2008 and 2014-15. During these two episodes the net worth of oil producers represented in the right plot of Figure 2 was severely impacted. The net income/assets ratio was impaired especially after the 2014-15 slump, where years of accumulating leverage, combined with a more protracted price downturn, made the fragile financial conditions of shale oil producer even more dramatic and called for a more pronounced attention to their financial sustainability by lenders. We use these wide oil price fluctuations as a source of substantial

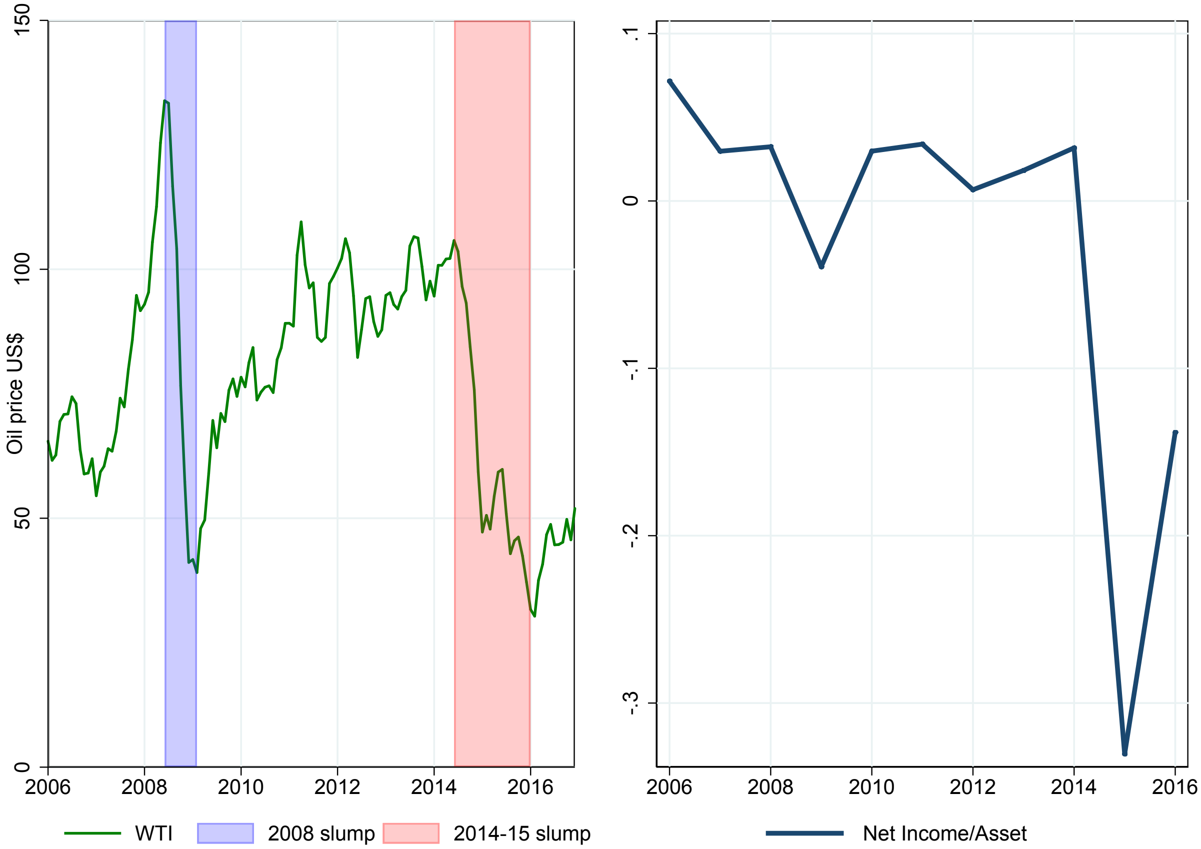

Figure 2
WTI price and net worth
The left plot displays the West Texas Intermediate (WTI) spot price with shaded area for the two significant oil price collapse in recent years; the series is from Datastream. The right plot displays median net worth defined as Net Income/Assets for selected US E&P companies; details on the firms included in the sample are available in Section 3.

variation in producers risk management strategies, through their effect on firms' net worth (see the left plot in Figure 2 for the dynamics of the WTI spot price in the last decade) to assess the intensity of the relation between hedging and net worth.[2] Interpreting these two dramatic oil price slumps as quasi-natural experiments, with a difference-in-difference approach we show how the shock to net worth differently affected the risk management practices among oil producers.

[2]We refer to Hamilton (2009), Kilian and Hicks (2012), Kilian (2014), Ellwanger et al. (2017), and Prest (2018) for some contributions explaining in detail the recent oil price dynamics and investigating the cause and consequences of the two oil slumps.

Finally, thanks to the wealth of information of our data set we are able to look into the particular contract chosen to hedge production and test whether net worth affects not only the hedging intensive margin but also the choice of the specific derivative category. This allows to further improve our understanding of hedging decisions by focusing also on the interlink between risk management motivations and contract characteristics, a theme that is not frequently investigated in the empirical research for scarcity of data. In this case we find a less evident relation linking net worth to firms' hedging strategies, though generally speaking our results points to a more limited use of linear derivative contracts when firms' net worth increases.

The rest of this paper is organized as follows. Section 2 reviews some of the theoretical and empirical contributions on firms' risk management, Section 3 describes the data set and the measures of net worth used to analyze firms' hedging strategies. Section 4 examines the main empirical results and discusses the identification strategy adopted to present evidence of a positive causal link between hedging and net worth. Section 6 supplements the analysis on hedging and net worth by analyzing how the latter impacts optimal risk management strategies. Finally Section 7 presents our conclusions.

2 Literature review

The literature has proposed a plenty of both theoretical and empirical contributions to explain risk management in non-financial firms. Departing from a classical Modigliani-Miller specification, we could generally claim that corporate hedging could be beneficial as long as it abates the impact of some market frictions including, but not limited to taxes, managerial risk aversion and compensation scheme, information asymmetries, costs of bankruptcy. In this paper, we explicitly focus on risk management as a result of costly external financing, a theme that was originally advanced in a seminal theoretical study by Froot et al. (1993). In absence of hedging, firms may be exposed to some variability in their internally generated cash flows which could potentially undermine their investment policies. To solve this problem firms can turn to 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 mitigate underinvestment. However, despite the appeal of their framework, little empirical evidence has been found for their model (Stulz, 1996).

Since then, several studies have analyzed the interlink between financial constraints constraints and risk management, and how this may limit the firms' ability to hedge. Holmström and Tirole (2000) investigate the determinants of hedging modeling jointly liquidity management, risk management and capital structure. The authors suggest that credit constrained firms can preserve internal funds and deliberately choose an incomplete insurance against liquidity shocks to maximize the marginal return on investments in case the shock does actually materialize. Mello and Parsons (2000) characterize optimal hedging strategies for financially constrained firms. In their model the optimal hedge minimizes the variability in the marginal value of the firm's cash balances, by redistributing them across states and time. They show that a departure from a condition of perfect hedge can negatively affect the firm's expected costs of financing, its financial constraints, and the corporate value. More importantly for our analysis, their framework predicts limited or incomplete hedging for severely constrained firms, thus reconciling with the empirical evidence of higher hedging intensity among larger firms.

A more explicit challenge to the framework of Froot et al. (1993) is available in Rampini and Viswanathan (2010) and Rampini and Viswanathan (2013) who examine how collateral constraints alter the dynamic trade-off between external financing and risk management. They challenge the study of Froot et al. (1993) by relaxing two crucial assumptions. First, they dynamically consider investment and hedging as two competing firms' decisions; second, they assume that both activities absorb collateral to cover promises to pay. Therefore, it is precisely when a firm net worth falls and the marginal value of its investments is high, that it may choose to forgo hedging so to invest its limited resources. Their model is empirically validated in the case of airline companies hedging commodity price risk, see Rampini et al. (2014). Hedging falls among more financially constrained airlines and more so as they approach distress: airlines prefer to pledge the scarce collateral to finance investments rather than hedging fuel price risk. More recently, Rampini et al. (2017) unveil a similar trade-off between financing and risk management for US financial institutions when hedging interest rate and foreign exchange risk.

Though the theoretical framework in Rampini and Viswanathan (2010) and Rampini and Viswanathan (2013) has been so far tested in the context of commodity risk management for firms hedging an input price (i.e. airlines), analyzing risk management in E&P US oil companies during 2006-2016 permits to extend the empirical research in this field from several perspectives. First, as discussed in Section 3, in these firms the exposure of revenues and assets to a volatile risk factor is definitely higher and can exacerbate firms' financial constraints by severely impairing their balance sheet positions and the value of their collateral. Second, in small independent E&P firms the scope of business is generally limited to mere oil extraction, thus excluding oil refinement activities that can represent a source of natural hedging for large vertically integrated firms Mackay and Moeller (2007). Third, during the time-span of our sample the oil market was hit by two sharp price declines whose effects were also combined with significant spikes in market volatility, as measured by the CBOE crude oil volatility index. This allows us to study the dynamic trade-off between external financing and risk management during a period of market turbulence. Indeed, this is of particular interest as price uncertainty may curb corporate capital investment, with an effect that is even amplified when it is associated with limits to firms' ability to hedge (Doshi et al., 2017).

In the context of the oil sector, some contributions have recently added to the empirical research by analyzing risk management from several points of view. A test of the effectiveness of financial risk management is provided in Gilje and Taillard (2017), who show how hedging is effective in reducing the probability of financial distress and underinvestment risk, thereby affecting also firm value. Following the widening of the spread between US and Canadian oil price benchmarks, Canadian firms more exposed to basis risk are shown to reduce investment, record falling valuations, sell assets, and reduce debt. Focusing on US oil producers, Gilje (2016) studies how collateral based financing may distort investment decisions and trigger risk shifting behavior. He exploits an exogenous variation in leverage, induced by two episodes of marked oil price falls, to show that more restrictive covenants or a shorter duration of debt mitigate the risk-shifting, as proxied by the share of expenses in exploratory drilling over total investment expenditure. Gilje et al. (2017) use detailed well-level data to unveil a debt related investment distortion which emerges when producers, in the face of falling oil prices and a futures curve in contango, rush to complete wells and exploration in order to increase the value of their collateral, so to improve their credit standing. This acceleration in well completion is more pronounced ahead of regularly scheduled renegotiations with creditors. Similarly, Lehn and Zhu (2016) show that, during 2011-16, more leveraged companies faced with collapsing oil prices and declining investment opportunities, still ramped up production to meet debt repayments. Such a debt-driven investment distortions may even hinder the downward adjustment in oil production as oil prices fall, thus reducing the supply elasticity of the otherwise more price sensitive shale producers.[3]

[3]When collecting data on hedging we came across multiple evidence of how tied is the connection of oil producers with financing banks also with respect to risk management. An example is found in Whiting's 2015 10-K report: "*Commodity derivative contracts held by the Company are with six counterparties, all of which are participants in Whiting's credit facility as well, and all of which have investment-grade ratings*

Along with the decision of whether and how much to hedge (*intensive margin*) firms need to choose how to hedge (*extensive margin*). To do so, oil producers can customize their risk exposure by resorting to a menu of derivative instruments and strategies. Compared to the intensive margin of hedging, fewer studies have looked into how firms effectively hedge, probably as a result of the the scarcity of firm-level information on derivatives portfolio. Limiting to commodity risk management, a seminal contribution by Tufano (1996) presents descriptive analysis on risk management strategies in gold mining firms, unveiling that the use of options is more frequent in large firms. Adam (2002) models firms' risk management in an inter-temporal setting to rationalize the firms' optimal decision in choosing between nonlinear and linear hedging strategies. His predictions are further explored in Adam (2009) who finds that options are prevalent in the gold mining industry, with financial constraints significantly increasing the likelihood of their adoption. Mnasri et al. (2017b) and Mnasri et al. (2017a) conduct an extensive analysis of the determinants and the value effect of nonlinear strategies for US oil producers. Finally, Croci et al. (2017) mainly focus on managerial preferences and risk incentives arising from executives' compensation schemes to describe the factors underpinning the optimal combination of derivative strategies. Our data set allows us to extend the analysis of derivative strategies in the oil market sector throughout a period including both new conditions in the financial markets (commodity financialization) and new producers relying on increasing leverage to lead the technological change in the oil production (shale revolution). In the following we will show that market dynamics have affected not only the extent of corporate hedging but also the mix between derivative contracts differencing in terms of payoff profile, cost structure, and complexity. In the last part of this study, we explicitly take into account collateral constraints for the choice of the hedging strategy by conditioning the extensive margin of linear derivatives to net worth measures as well as to a wide spectrum of firms' characteristics.

3 Data

In this Section we first describe the process of data collection based on hedging disclosure available in firms'annual report (10-K). Then, we provide some statistics on the derivative contracts employed to cover oil production and we define our measure of hedging activity. Finally, we present some possible measures of net worth that are used in the following

from Moody's and Standard & Poor. As of December 31, 2015, outstanding derivative contracts with JP Morgan Chase Bank, represented 76% of total crude oil volumes hedged.".

empirical analysis.

3.1 Data sources

To study the relationship between net worth and hedging we rely on a new firm-level dataset providing detailed information on E&P hedging strategies. More precisely, we hand-collected data for the period 2006-2016 on the notional amount of each hedging contract, as well as on the different type of contracts used to hedge the oil production. This information comes from annual company reports, available from the EDGAR website. First, we extract from Compustat the US companies classified with Standard Industrial Classification (SIC) code equal to 1311 (Crude petroleum & Natural gas) in the period 2006-2016. According to this criteria, there are 686 unique firms with primary activity in "Crude Petroleum and Natural Gas" exploration and production. Second, from this initial list we exclude those with either no publicly available 10-K on EDGAR, or with less than five years of reports.[4] Third, we further filter out smaller reporting company that are not required to disclose information as their market risk is considered as negligible.[5] This leaves us with 167 unique firms. Finally, we exclude those where risk management practices 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". At the end of this filtering procedure we obtain an unbalanced sample of 102 unique firms observed over an 11 years time period. Some descriptive statistics on oil production, reserves and firm characteristics are shown in Table 1.

The firms in our final dataset account for approximately 30% of overall US oil production and are especially representative of small independent producers, including shale firms.[6] This can be better grasped by comparing production obtained from our firm-level dataset with the one obtained from the US EIA statistics for shale regions. The evolution of production in the right plot of Figure 3 closely tracks the one of shale oil production presented in Figure 1, corroborating our choice of the sample to study firms which adopted shale technology. In the peak year of 2015, production reached 3.5 mbd when measured from our firm-level data, approximately 4.8 in the EIA statistics on shale production.

[4]This last choice is primarily motivated to ensure a minimum coverage of hedging practices over the period of analysis and make our dataset suitable to study within-firm evolution in risk management.

[5]We refer to the SEC website for further details on the definition of smaller reporting companies https://www.sec.gov/smallbusiness/goingpublic/SRC.

[6]Major oil companies such as Chevron or Exxon Mobil, are not included in our sample, as they are generally classified in the 2911 SIC "Petroleum Refining".

Table 1
Firms' summary statistics

	N	Mean	St.Dev.	25p	50p	75p
Oil production (Mb/d)	938	7.2	15.2	0.1	1.1	6.5
Oil reserves (MMb)	926	92.3	206.2	1.6	15.1	77.2
Production mix	941	44.9	31.2	16.4	42.3	70.0
Revenues (M$)	944	1639.2	5319.9	44.0	296.1	1068.3
Property plant (M$)	926	4136.0	8506.4	133.5	1025.6	3135.8
Capital expenditure (M$)	962	976.6	1948.7	29.0	269.7	923.8
Employees	892	1033.5	2792.2	39.0	211.5	780.5

The table presents summary statistics for US E&P companies; data refer to firm-year observations. *Oil production* is crude oil produced measured in thousands of barrels per day; *oil reserves* is US proven developed and undeveloped reserves of crude oil held by the company at year-end, in millions of barrels; *production mix* is crude oil production as a percent of the company's total oil and gas production both measured in terms of barrel of oil equivalent; *revenues* is oil and gas revenues in US$ millions; *property plant* is net value of property, land, and other physical capital in US$ millions; *capital expenditure* is the amount spent on purchases of tangible fixed assets related to E&P activities in US$ millions; *employees* are firm total employees.

The right plot of Figure 3 presents the median ratio between the value of net property and equipment (including oil and gas properties) over total assets. Oil and gas properties, which are largely made of proved reserves, represent a paramount component of total firm assets, with a median value larger than 80% across firm-years observations. The annual median value always fluctuates above 75%, with two sizable declines during the 2008/9 and the 2014/15 price slumps. In view of the limited size of non-oil related assets and revenues, this underscores the importance of the oil price in affecting producers' net worth and their borrowing capacity, which strongly reinforces the interplay between dynamic risk management and collateral availability, first described by Rampini et al. (2014). In their empirical application, airline companies need to hedge fuel oil costs, which account, on average, for between 20-30% of total operating costs, and firms pledge their assets (aircrafts) to borrow. In our case, oil producers need to hedge their output, and pledge oil reserves, both of which depend on the oil price.

3.2 Net worth measures

As the primary focus of this study is to test the impact of collateral constraints on hedging activity, we augment the data set to include information about firms' net worth. From this

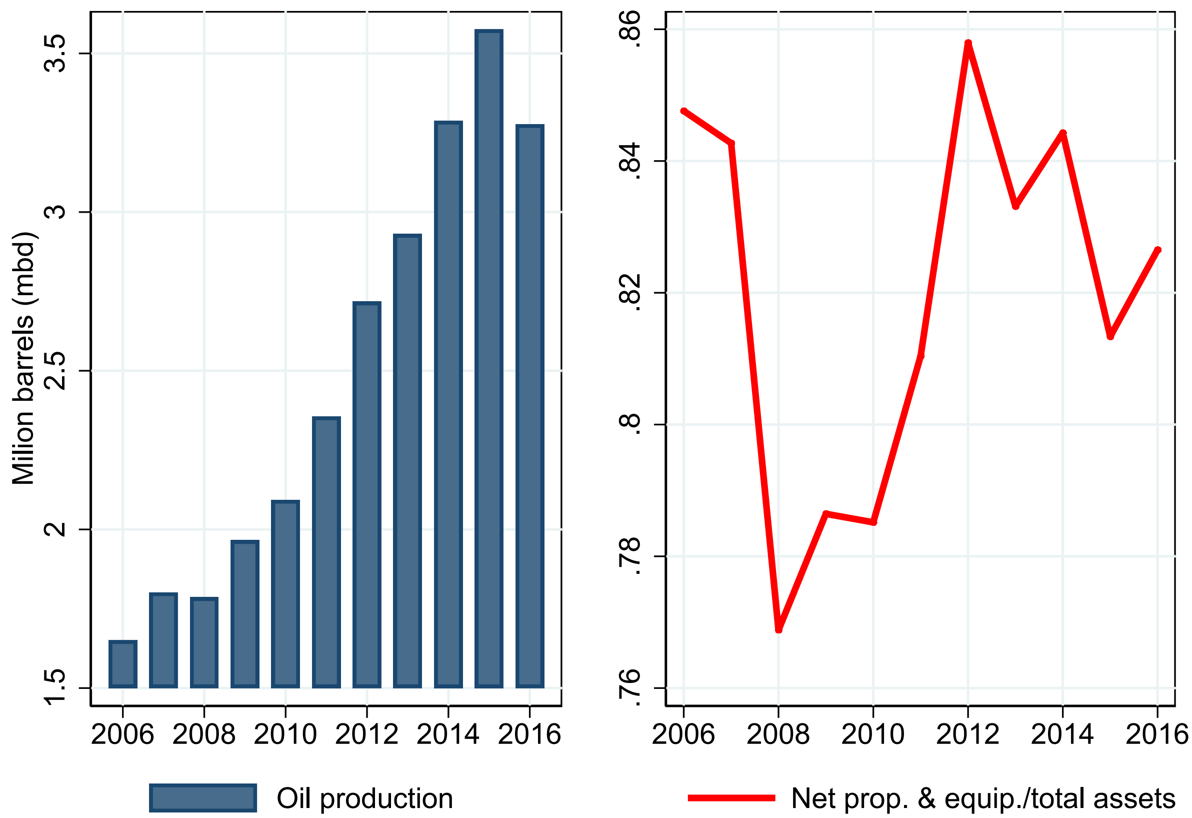

Figure 3
Oil production and relevance of oil related assets
The left plot displays the total oil production in mbd of E&P firms included in the sample. The right plot shows the median ratio between net property and equipment over total assets; net property and equipment include oil and gas properties net of accumulated depreciation, depletion and amortization

perspective, we acknowledge that a correct identification of net worth represents a fundamental task for an empirical research analyzing the interplay between risk management and firms' financial constraints. Unfortunately, this purpose conflicts with the absence of an unambiguously accepted definition of net worth and in principle different measures of financial constraints could be accepted. For this reason, we partially follow previous studies in this field and use several balance sheet and market-based variables to construct a set of possible net worth indicators. This allows us to emphasize the robustness and consistency of our findings confirming that they are not subordinate to a specific measure. To this end, we combine firms' hedging data with a comprehensive list of financial and accounting variables retrieved from Bloomberg. We consider the following measures of net worth: net income/assets, the market value of equity (market capitalization), the ratio between the book value of equity and total assets, the book value of assets (size), and two market based measures implied by the Bloomberg Issuer Default Risk model, namely the 5 Year CDS and the 1 year probability of default.[7] Descriptive statistics on net worth measures and firm leverage are reported in Table 2. Some net worth measures exhibit larger skewness and heterogeneity as concerns

Table 2
Net worth summary statistics and leverage

	N	Mean	St.Dev.	25p	50p	75p
Net Income/Assets	945	-0.08	0.32	-0.09	0.01	0.06
Market cap.	881	6.60	2.14	5.22	6.72	8.15
Size	968	6.78	2.27	5.33	7.21	8.30
Equity/Assets	968	0.45	0.41	0.37	0.48	0.64
Bloomberg 5YR CDS	741	2.65	3.31	0.91	1.64	2.91
Bloomberg 1YR PD	760	1.20	3.14	0.01	0.11	0.81
Leverage	961	0.32	0.34	0.12	0.27	0.42

The table presents summary statistics for various new worth measures: *net income/assets* is net income divided by assets, *market capitalization* is log(number of shares*end of year price), *size* is log(assets), *equity/assets* is the book value of common equity divided by assets, *Bloomberg 5YR CDS* is 5 Year credit default swap spread for the company implied by the Bloomberg Issuer Default Risk model, *Bloomberg 1YR PD* is the probability of default of the issuer over the next 1 year calculated by the Bloomberg Issuer Default Risk model. *Leverage* is total debt divided by assets.

the frequency distribution, more so when considering net income/assets and the two market based indicators retrieved from Bloomberg. For these three measures the sample mean is quite far from the corresponding median and the distribution is quite dispersed. To a large extent this finding results from the two oil price slumps within our sample, which especially impacted on the market measures of net worth. In particular, the negative average value displayed for net income/asset reflects the severe net worth impairment experienced by some E&P companies during the two recent oil slumps reported also in the right plot of Figure 2.

[7] In some robustness tests we also try additional net worth measures including: cash dividends/assets, Bloomberg probability of default over the next 5 years, market value of equity/assets. The results are qualitatively similar and available upon request.

3.3 Derivative contracts

A benefit of examining the oil and gas industry is that disclosure of firms' derivative portfolios is remarkable. In particular, most firms provide information on each derivative contract, detailing the notional amount, the contract type, and maturity. Unfortunately this information is not presented in a standardized fashion, and data needs to be first hand collected and then reformatted. Starting from companies' 10-K report, we collect the information about the specific contracts used to hedge oil annual production.[8]

We then classify hedging instruments reported by companies in 8 distinct categories: futures/forward, swaps, collars, 3-way collars, swaption, call options, put options, and other derivatives including residual contracts. Table 3 displays the distribution frequency of the main class of financial instruments used to cover their 12-month ahead oil production. First of all, the table shows that about one third of the sample firms, in general the smallest producers in terms of size, are not engaged in risk management activities, with a remarkable peak around the 2008 oil slump. Moreover, hedging activity tends to be clustered into a limited number of derivative instruments, namely swaps, collars and three way collars.[9] Finally, the table also shows an apparent variability over time in terms of the hedging strategy. This indicates that firms' dynamic risk management entails decisions not only with respect to the notional amount to be hedged but also in terms of optimal derivative contract.[10]

The second and third columns of Table 3 include hedging instruments that are classified as linear hedging contracts, i.e futures/forward and swaps. While the frequency of use of futures/forward contracts is marginal or nil for most of the years, swaps represent the most common hedging tool, around 50% over the full sample, peaking at 62% in 2013. The class of nonlinear contracts is very heterogeneous: it embraces multiple financial instruments with very different payoff structures. Among these, the importance of collars has remarkably shrunk over time, ranging from almost 50% at the start of the period to 23% in 2016.

[8] Being our focus on US oil producers, we only consider derivatives where the WTI is the price benchmark of the contract. These derivatives represent, for the firms in our sample, the most comprehensive category of contracts adopted to hedge oil production if not the totality itself.

[9] The analysis of how firms choose a specific derivative contract is out of the scope of this study, though Section 6 investigates the role of financial constraints as a determinant of general risk management strategies. Broadly speaking, firms may choose swaps to completely eliminate risk exposure, both upside and downside. On the other hand, collar and three way collar could be preferred to options because of their cost structure as well as because they maintain some degree of (probably desired) risk exposure (see Adam, 2009).

[10] Firms could in principle enter into derivative transactions to achieve a trading profit: however, from the majority of 10-K collected, companies explicitly indicate that their goal is to reduce the effect of oil price fluctuations as a leading motivations for engaging in derivatives transactions.

Table 3
Hedging choice and derivative contracts

	No hedging	Linear contract		Non-linear contract					
		Futures	Swap	Collar	3-way collar	Swaption	Call option	Put option	Other
2006	36.5	1.3	43.5	49.7	1.9	0.0	0.0	3.7	0.0
2007	36.0	0.0	46.1	43.5	4.5	0.0	0.6	0.1	5.2
2008	50.6	0.0	53.0	36.3	5.0	0.0	1.0	0.2	4.6
2009	44.3	0.0	54.2	37.2	4.5	0.0	0.6	0.7	2.8
2010	40.0	0.0	42.5	42.4	6.0	0.8	3.5	3.3	1.5
2011	32.7	1.5	44.5	34.7	9.1	0.3	2.1	2.8	5.1
2012	31.3	1.5	56.1	23.9	11.7	0.9	1.1	1.5	3.4
2013	28.4	0.0	62.0	18.9	10.6	0.7	1.5	2.4	3.8
2014	34.7	0.0	57.1	16.5	12.7	0.6	2.9	4.5	5.6
2015	38.0	0.0	43.2	22.0	17.2	0.0	5.9	6.7	5.0
2016	38.4	0.0	50.0	23.2	15.5	0.1	1.9	4.5	4.9
Total	37.1	0.4	50.8	30.1	9.5	0.4	2.0	2.8	3.9

The table displays the frequency of non-hedging firms and the frequency of use of different categories of hedging contracts. The table presents average values computed with respect to all firms reporting in a specific year; all values are in percentage. Category "Other" includes residual hedging instruments such as put spreads, enhanced swaps, fixed-price contracts which are not covered in specific categories.

Their decline has been almost entirely offset by the increase in the share of 3-way collars. Plain vanilla instruments, such as call and put options, have gained some use in the most recent years but remain marginal (5% on average in the full sample). Finally, residual financial instruments are used to cover almost 4% of the oil production, while the presence of swaptions is almost insignificant.

To study the hedging strategies of oil producers, we need to define a measure of production hedged. Rather than an indicator simply signaling the use of derivative contracts (Guay and Kothari, 2003), we construct an indicator measuring the intensive margin of firms' hedging activity as in Haushalter (2000). More precisely, we start from the notional amounts reported over all hedging contracts to cover the 12 month ahead oil production and define an annual ratio for the fraction of production hedged $HR12_it$ as follows:

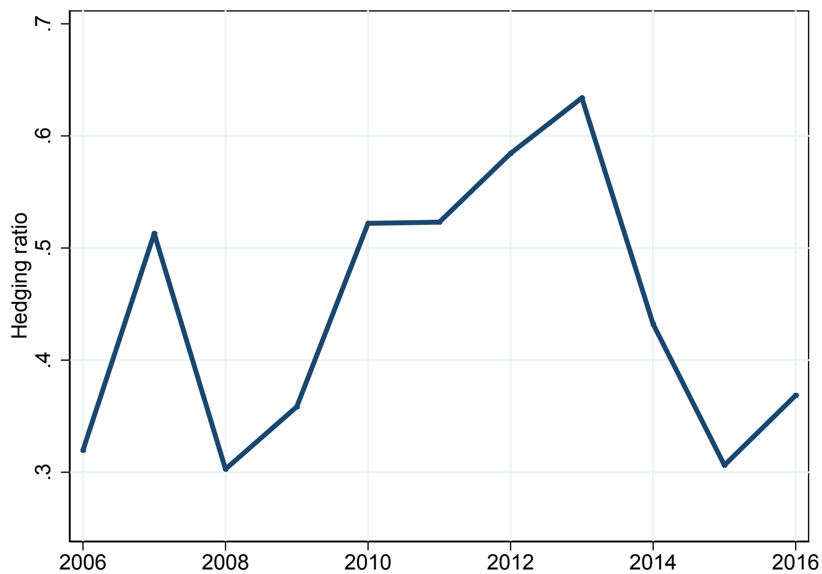

Figure 4
Sample hedging ratio
The graph displays the dynamics of the sample average hedging ratio which is defined as the ratio between total notional amounts reported over all hedging contracts to cover the 12 month ahead oil production and the oil production effectively achieved by the firm.

$$HR12_{it} = \frac{\sum_j Notional_{jit}}{Oil\, production_{it}}$$

where $Notional_{jit}$ is the amount of hedged oil barrels for derivative contract j at time t as reported in the 10-K of firm i, while $Oil\, production_i t$ represents the annual oil production effectively achieved by the firm i. Figure displays the dynamics of the sample average hedging ratio $HR12_t$ for the E&P firms included in the sample. The average share of oil production hedged is 45% across firm-year observations, though with some skewness and variability in the whole sample. Average $HR12_t$ recorded two marked reductions following the oil price slumps (2008 and 2014/15), whereas hedging increased between these two episodes fostered by rising production and fairly stable oil prices. This finding does not, per se, allow us to draw any final conclusion on the causal relation between firms' net worth (closely determined by oil prices) and risk management; yet it presents some preliminary empirical evidence of an inverse relationship between the intensity of hedging and oil prices.

4 Hedging and net worth

The key assumption in Rampini and Viswanathan (2010) and Rampini and Viswanathan (2013) is that collateral constraints apply to both external financing and hedging activity. Hence, managers face a trade-off: they can either engage in hedging motivated by risk aversion concerns or they can preserve resources to increase their investments, more so when firms' net worth is low and marginal productivity of capital is higher. A vivid example of this trade-off is provided by the dramatic decision of Continental Resource to settle, in the aftermath of the 2014 oil price slump, all of its derivative contracts prior to expiration. In doing so the company remained completely unhedged and exposed to volatility in crude oil prices but at the same time was able to cash in the gains on its existing derivatives and fund its drilling programs.

In this Section we investigate if and how different measures of firms' net worth are positively related with firms' hedging activity. Our specification is based on the following baseline equation:

$$HR12_{i,t} = \alpha + \beta NW_{i,t} + \epsilon_{i,t} \tag{1}$$

where for each firm i, $HR12$ represents the hedging ratio (production hedged as a ratio of total production) for the 12 month ahead and NW is one of the net worth measures defined in Section 3.2; t denotes time measured in years. In general, if the crowding out effect between hedging and collateralized financing is active, we would expect β to be positive and statistically significant. Clearly, a negative relationship would hold for our market-based measures of default risk, such as *Bloomberg 5YR CDS* and *Bloomberg 1YR PD*, which are inversely related to the firms' net worth.

We present in Table 4 the results for the empirical specifications of interest. All models include firm fixed effects to account for the effect of time-invariant unobserved firm characteristics (e.g. managerial risk aversion, risk management skills) on hedging policies.[11] The first column of Table 4 presents fixed effect panel estimates and provides some strong evidence of a direct relationship between net worth and the amount of hedging: all coefficients display the expected sign at the 1% significance level except for size that is significant only at the 5% level. The magnitude of the effect varies across net worth measures (shown row-wise), but is economically relevant. For example, and with reference to the first column of Table

[11] As a robustness check we also estimate a weighted least square specification and a tobit model to take into account the mass of firms signaling no hedging activity. The results are qualitatively similar and available upon request.

Table 4
Net worth and hedging

	(1) Panel est.	(2) Panel est. year FE	(3) First difference	(4) No crisis years	(5) No default. firms	(6) Only default. firms
Net Income/Assets	0.231***	0.163**	0.139**	0.375***	0.188***	0.407**
	(0.06)	(0.07)	(0.07)	(0.14)	(0.05)	(0.17)
Market cap.	0.086***	0.043*	0.114***	0.083***	0.096***	0.034
	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.07)
Equity/Assets	0.190***	0.139**	0.094**	0.239	0.245***	0.130**
	(0.06)	(0.05)	(0.04)	(0.15)	(0.09)	(0.05)
Size	0.080**	0.073*	0.204**	0.112**	0.057	0.167**
	(0.04)	(0.04)	(0.09)	(0.05)	(0.04)	(0.07)
Bloomb. 5YR CDS	-0.019***	-0.013**	-0.012**	-0.024**	-0.017***	-0.049*
	(0.00)	(0.01)	(0.01)	(0.01)	(0.00)	(0.03)
Bloomb. 1YR PD	-2.443***	-1.566*	-1.375*	-3.194**	-1.908**	-5.078***
	(0.84)	(0.82)	(0.78)	(1.42)	(0.78)	(1.72)

The table presents regression coefficients for the equation relating firms' hedging ratio and net worth. All models include firm fixed effects. Robust standard error in parentheses. Dependent variable is 12-month ahead hedging ratio; $HR12$ is equal to zero for non-hedging firms. *, **, and *** denote significance at, respectively, the 10%, 5% and 1% level. *Net Income/Assets* is net income divided by assets, *Market Cap.* is log(number of shares*end of year price), *Size* is log(assets), *Equity/Assets* is the book value of common equity divided by assets, *Bloomberg 5YR CDS* is 5 Year credit default swap spread for the company implied by the Bloomberg Issuer Default Risk model, *Bloomberg 1YR PD* is the probability of default of the issuer over the next 1 year calculated by the Bloomberg Issuer Default Risk model. Column 4 displays estimates excluding the years of oil price collapse (2008, 2014, 2015). Defaulted firms include: Berry Petroleum, Emerald Oil, Energy XXI, Escalera Resources, Goodrich Petroleum, Magnum Hunter Resources, Miller Energy Resources, Osage Exploration & Development, Postrock Energy, Sabine Oil & Gas, Sandridge Energy, Stone Energy, Ultra Petroleum.

4, a one standard deviation increase in net worth implies an increase in the hedging ratio varying on the basis of the net worth measure and ranging between about 6% (Bloomberg 5 YR CDS) and more than 18% (Market capitalization)[12]. To fully exploit the within-firm variation in hedging behavior and rule out serial correlation effects we consider two different specifications: first, by including annual fixed effects (column 2); second, by considering the

[12]Similar, and sometimes even larger effects, are found for all the empirical specifications displayed in Table 4; results are available upon request.

baseline specification estimated in first differences (column 3). Albeit the statistical and economical significance of our results is somehow weakened, the estimated coefficients still point to a substantial effect across all net-worth measures.

To check whether our results are driven by the years with falling prices, affecting firms' net worth and forcing managers to reduce hedging and prefer borrowing when collateral is scarce, we also re-estimate the same specification by selecting specific sub-periods. When we exclude the oil price slump years (2008, 2014, 2015, model in column 4), we actually find that the opposite is true, as the standardized effect of net worth on hedging is generally even larger. In the same spirit, in the last two columns of Table 4 we test the model by splitting the sample between firms which never defaulted in our sample (column 5) and those which have defaulted (column 6).[13] This is to check if the results reported in columns (2)-(4) are driven by distressed firms included in the sample. Indeed, we would expect defaulted firms to have reduced more intensely their hedging, as collateral constraints become even more binding in this case. The estimates in Columns 5 and 6 seem to rule out also this possibility, though the statistical significance of estimates referred to defaulted firms is not always very strong, which is not surprising in light of the considerably smaller number of observations used.

In general the findings presented in this Section provide, in the context of US oil producers, a strong empirical validation of the link between net-worth and hedging, emphasized by modern dynamic risk-management theories. This result is remarkably robust both across the range of net-worth measures considered and various model specifications.

5 Tackling endogeneity

In the previous Section we showed that less financially constrained firms engage more in risk management activities. Though this relation seems robust across multiple model specifications and definitions of net worth, omitted variable bias and simultaneity may represent a potential concern. In this Section we address this issue. First, we present instrumental variable (IV) estimates using an identification strategy that exploits E&P firms' main source of net worth, namely oil reserves, as well as a measure of firms' operational efficiency. Second, we employ the oil price declines in 2008 and 2014-15 as quasi-natural experiments to show

[13] We consider as defaulted the following firms filing for bankruptcy: Berry Petroleum, Emerald Oil, Energy XXI, Escalera Resources, Goodrich Petroleum, Magnum Hunter Resources, Miller Energy Resources, Osage Exploration & Development, Postrock Energy, Sabine Oil & Gas, Sandridge Energy, Stone Energy, Ultra Petroleum.

how companies remarkably reduced their hedging activity, as they became more financially constrained when hit by these two severe shocks to revenues.

5.1 Instrumental variable estimates

For the IV exercise we focus on net income/assets among the possible measures of net worth. This indicator is a flow variable which successfully captures net worth variations as a consequence of oil price dynamics (see Figure 2). Moreover, to rule out spurious results because of variations in the operating scale of the company, this measure is also standardized by total assets. We consider two possible instruments for net worth. First, we rely on an identification strategy that uses changes in reported oil reserves as a source of idiosyncratic variation in the firms' net worth.[14] Oil reserves account for a substantial fraction of E&P companies' net worth and represent the principal asset component in their balance sheets, as depicted in Figure 3. Moreover, oil reserves define the common source of collateral in the context of the so called "reserve base lending", i.e. the standard financing process of E&P firms where the amount of money granted is proportional to the extent of proven oil reserves (Domanski et al., 2015, Azar, 2017). To construct our first instrument, we exploit a unique feature of companies annual reports, which provide detailed information of the factors driving changes in the amount of proved oil reserves: acquisitions, sales, extensions and new discoveries, production, and revaluation. This allows to discriminate between changes in net-worth due to managerial decisions (e.g. to drill more to expand the reserve base) and hence tightly related to the hedging decision, from those "sufficiently" exogenous to the firms decision. To this end, we focus on the variation in reserves due to the revaluation component and compare this item to the total amount of reserves available to the firm. Based on SEC definition *"Proved O&G reserves are quantities of petroleum that, by analyzing geological and engineering data, are reasonably certain to be commercially recoverable from a given date forward from known reservoirs and under current economic conditions, operating methods, and government regulations"*. In other words, the reserve revision item accounts for variation in the total amount of reserves due to factors such as updated reservoir analysis, well performance, and especially variation in oil prices; indeed, we find extensive anecdotal evidence in the companies' 10-K that changing economic conditions are the main driver of annual reserve revision.[15]. Hence, our first instrument for net worth is defined as:

[14] A similar strategy is used in Gilje (2016).

[15] For the sake of brevity we report only some examples included in the following 10-K: Carrizo (2015): *Crude oil, condensate and natural gas liquids revisions of previous estimates are primarily attributable to the following: 2015 negative price revisions as a result of the significant decrease in the oil price used to calculate*

$$Instrument\,1 = \frac{Reserves\,Revision}{Reserves}$$

where *Reserves Revision* quantifies the variations in reserves due to exogenous factors and *Reserves* represent the amount of company's oil reserves (both variables are measured in physical oil barrels). Our identification strategy is based on the assumption that variation in oil reserves, net of the production component and other recomposition effects driven either by sales or purchases of properties, should affect the intensive margin of hedging through their impact on the firm's net worth. In fact, oil price dynamics exogenously determines a revaluation of reserves which is unrelated to managerial decisions potentially affecting other firms' characteristics, such as risk management practices. Nevertheless, in order to mitigate residual concerns on endogeneity, in the IV estimation we also control for oil market conditions and firms' oil production.

Second, as an alternative instrument, we consider a firm-level efficiency indicator of the exploration activity. In principle, we expect more productive firms to be also the ones with higher net worth. Our identification strategy hinges on the assumption that drilling efficiency, arguably a dimension of productivity relating to the physical and geological characteristics of the oil fields being drilled, while affecting firms' net worth should not be linked to the financial management decision.[16] To this end, we use an indicator of well efficiency defined as follows:

$$Instrument\,2 \equiv Well\ efficiency = \frac{Gross\,Productive\,Wells}{Employees}$$

where *Gross Productive Wells* represents the number of wells producing, or capable of producing, oil at year-end including also the wells in which the company has a full or partial interest, while *Employees* is the number of company's workers. To deal with potential endogeneity, in this case we control for factors related to firms' drilling activity, such as capital

our proved oil reserves estimates of 11,194 MBbls, partially offset by positive performance revisions of 4,904 MBbls.; Pioneer (2012): *at December 31, 2012, revisions of previous estimates are comprised of 82 MMBOE of negative price revisions and 27 MMBOE of negative revisions due to updated performance profiles and cost estimates*; Continental resources (2015): *Commodity prices decreased significantly in 2015 [...] These decreases shortened the economic lives of certain producing properties and caused certain exploration and development projects to become uneconomic which had an adverse impact on our proved reserve estimates, resulting in downward reserve revisions of 185 MMBls [...]. We may experience additional downward reserve revisions as a result of prices in 2016 if the currently depressed price environment for crude oil and natural gas persists or worsens.*

[16] In Rampini et al. (2014) the authors instrument net worth with changes in productivity as proxied by firms' operating income. Mansell et al. (2012) show that the average cost per well drilled is lower among larger E&P firms.

Table 5
IV regression - instrumenting net worth with reserves and well efficiency

	First stage equation		
	IV1	IV2	IV1-IV2
Instrument 1	0.292**		0.149**
	(0.11)		(0.06)
Instrument 2		0.015***	0.020***
		(0.00)	(0.01)
F statistics	8.831	20.828	11.682

	Second stage equation			
	Panel	IV1	IV2	IV1-IV2
Net Income/Assets	0.231***	0.369**	0.437***	0.494***
	(0.06)	(0.19)	(0.16)	(0.17)
Hansen J p-value	–	–	–	0.868

IV regression with instrumented net worth measures and firm fixed effects; robust standard errors in parentheses. Dependent variable is net income / assets in the upper panel (first stage equation) and $HR_1 2$ in the lower panel (second stage equation). In Column IV1, net worth is instrumented via Instrument 1 ($Reserve\,Revision/Reserves$), while in IV2 net worth is instrumented via Instrument 2 (*Well efficiency*); in Column IV1-IV2 both instruments are jointly included in the specification. Controls in IV1 regression include the annual average of the CBOE Crude Oil Volatility Index (CBOE oil vix), the annual average calendar strip on WTI, and the firm's crude oil production. Controls in IV2 regression include firm-level measures of costs incurred for E&P activities, capex expenditures, business efficiency per employee (EBIT/employee), drilling success rate, and crude oil production. All the controls in IV1 and IV2 regressions are included in the joint estimation IV1-IV2. *, **, and *** denote significance at, respectively, the 10%, 5% and 1% level.

expenditures and success rate in the development of new oil wells.

Our IV estimates (2SLS) are reported in Table 5. The upper panel presents the results from the first stage regression: all the three specifications display a positive correlation between net worth and our proposed instruments, which still holds when they are jointly considered (column IV1-IV2). Also the F-statistics from the reduced form equations points to an adequate relevance of revision in oil reserves and drilling efficiency as instruments for net worth.[17] In the lower panel of Table 5 we provide the second stage estimates of the link between risk management and instrumented net worth; for ease of comparison we also

[17] Admittedly, the F-statistics in the IV1 specification is marginally lower than the common applied threshold of 10. Though this could potentially mask a problem of weak identification, we note that the value of our F-statistic is also remarkably impacted by the adoption of clustered standard errors.

report, in the first column, the estimates obtained earlier when net worth was proxied by net income/assets in Table 4. As anticipated, all specifications are augmented by a set of regressors accounting for oil market conditions, firm investments, crude oil production, and drilling activity. The evidence in Table 5 confirms the theoretical prediction of a positive causal relation linking net worth to hedging. All the IV estimates are qualitatively comparable with those previously reported in Table 4. However, the magnitude of the effect estimated by IV is generally larger than the one previously obtained; this results points to a possible measurement error attenuation respect to the panel estimate.[18] Finally, for the combined specification IV1-IV2 we also report the Hansen J-statistics for the test of overidentifying restrictions, which does not reject the null hypothesis of validity of our instruments. Overall, the findings in Table 5 seem to validate our identification assumptions based on variations to operational efficiency and the value of oil reserves, as two factors affecting risk management practices through their impact on firms' net worth.

5.2 The role of leverage and credit constraints

In the following we shed further light on the relationship between net worth and risk management. To this end, we exploit the two oil price collapses in our sample, i.e. the 2008 and 2014-15 oil price slumps, as quasi-natural experiments. These oil price declines were an exogenous and dramatic shock to oil companies' net worth which markedly impaired their borrowing capacity. If higher net worth is indeed a key factor driving the interplay between hedging and collateralized external financing, we would expect a decrease in hedging for firms more deeply affected by the commodity shocks. As pointed out by Mello and Parsons (2000), every hedging strategy comes packaged with a borrowing strategy. Suggestive evidence for a tight link between between credit and hedging decisions comes from the 2015 10-K filing from Whiting: *the credit agreement contains restrictive covenants that may limit our ability to, among other things [...] enter into hedging contracts, incur liens and engage in certain other transactions without the prior consent of our lenders.*

We resort to a difference-in-differences strategy (DID), where we separately test the effect of the two price declines by symmetrically splitting our data range in 2011.[19] This

[18] At least for IV1 where net worth is instrumented via exogenous variation in reserves, we stress that a full comparison cannot be achieved as data on oil reserves are available for the whole sample starting from 2010.

[19] The main results discussed in this Section are qualitatively similar with different choices of the splitting year (e.g. 2010 or 2012) as well as if we exclude observations during the oil slumps years (2008, 2014, 2015). The full set of estimates is available upon request.

choice allows to take into account two important issues. First of all, firms may have been differently affected by the two oil collapses, so assuming a dynamic treatment threshold is fundamental for dealing with the time-varying classification of firms (treatment vs control) in the two events and with sample attrition because of bankruptcies. Second, starting from 2010-2011 E&P companies have been facing not only a technological development with shale oil boom but also a profound transformation of their financial structure as reported in Figure 1. Therefore, by splitting the sample in two periods allows to appreciate the impact of the buildup in debt observed during the shale revolution.

We proceed by assuming a within-event matching, and we construct treatment and control groups on the basis of the companies net worth in the year prior to the crisis. For example, in the DID regression for the 2008 oil slump, a firm is considered as treated when its net worth measured by net income/assets is below the median value of the sample net worth in 2007. A similar strategy is adopted for the 2014-15 case, using the median net worth in 2013.[20] The effect of a commodity shock on the hedging ratio of firms is evaluated through a DID setting according to the following regression form:

$$HR_{it} = \alpha + \beta_1 Post + \beta_2 Treatment_i + \beta_3 Treatment_i \times Post + \epsilon_{it} \tag{2}$$

where $Post$ is a dummy variable equal to 1 starting since the occurrence of the commodity shock (2008-2011 or 2014-2016), while $Treatment$ is another dummy variable that is equal to 1 for firms classified as treated, i.e. with net worth below the sample median. In the DID regression the coefficient of interest is the one of the interaction term, β_3. This coefficient measures the difference between pre-shock and post-shock hedging behavior for treated firms relative to firms whose net worth is less deeply affected by the decline in oil prices. Table 6 displays the DID estimates for the two episodes, with the 2008 results in the top panel and those for 2014-15 in the bottom panel, respectively. Bearing in mind that oil-related assets account for the lion's share in E&P companies net worth we would expect, in line with theoretical predictions, the interaction coefficients (β_3) to exhibit a negative and statistically significant sign. This is indeed what emerges from Table 6, confirming the causal link between net worth and hedging. In both episodes, the magnitude of the effect is also economically relevant and comparable to the one reported in Table 4.

The significance of this additional reduction in hedging for firms with lower net worth is robust to the inclusion of additional variables accounting for firm leverage and short-

[20] In both episodes we also tried different thresholds for net worth, e.g. percentiles ranging in the interval 50-75. The estimates are qualitatively similar to the median case and are available upon request.

Table 6
Difference in difference estimates

	2008 oil slump			
	1	2	3	4
Year>=2008× Treated NW	-0.264**	-0.273**	-0.275*	-0.256**
	(0.123)	(0.127)	(0.144)	(0.116)
Short term obligations		0.150		
		(0.201)		
Available Credit lines			-0.011	
			(0.048)	
Leverage				-0.251
				(0.543)
	2014-15 oil slump			
	1	2	3	4
Year>=2014× Treated NW	-0.186**	-0.176**	-0.174*	-0.182**
	(0.093)	(0.088)	(0.099)	(0.091)
Short term obligations		-0.113***		
		(0.008)		
Available Credit lines			0.066**	
			(0.027)	
Leverage				-0.130**
				(0.055)

Difference-in-differences estimates with firm fixed-effects. Robust standard error in parentheses. Dependent variable is 12-month ahead hedging ratio. A firm is considered as treated when its net worth measured by net income/assets is below the median value in the year prior to the 2008 or 2014-15 oil price shocks, respectively. *Short term obligations* represent all debt and payments due within one year, *available credit lines* represent the unencumbered fraction of credit lines granted to the firm, *leverage* is measured as total debt/assets *, **, and *** denote significance at, respectively, the 10%, 5% and 1% level.

term debt constraints. Controlling for this credit dimension is not only relevant to explain the transformation in the financial structure of oil firms, but it is also crucial in order to account for other factors affecting firms' hedging decisions. To this end we consider separately, to avoid collinearity issues, three measures of financial constraints: short-term obligations which measure the amount of obligations expiring within one year, available credit lines that provide information on the fraction of unencumbered bank borrowings, and leverage defined as total debt/assets. The two last variables control, respectively, for short-term commitments that could curb additional risk taking and for unused debt capacity which could enhance firm liquidity. When we augment the baseline DID regression with the proxy of firms' indebtedness we continue to find a significant effect of net worth on hedging. However, comparing the estimates across the two panels of Table 6, we find that the additional controls for "credit constraints" display a statistically significant coefficient only in the second episode, and at the same time also the magnitude for the interaction term is somewhat dampened. One potential explanation for this result can be sought again via the graphical insight presented in Figure 1 and Figure 2. The second price fall stroke the oil industry after a period of increasing debt accumulation driving the expansion of shale oil production (Domanski et al., 2015). As an example, the leverage ratio in 2013 was about 8 p.p. higher than the 2008 value, peaking to a level 16 p.p. higher in 2015 after the fall in output prices. The surge in leverage and the differences in financial conditions become more apparent in the second half of the sample span, making firms more financially constrained and close to distress which could explain the different outcome for the two oil shocks. In other words, starting from 2010 the burden of the debt component in the "collateral call" has become larger and showed up also directly in the leverage variables, while earlier the same effect was not apparent.[21]

To check the validity of our quasi-natural experiment and validate the causal interpretation of results, we end this Section by presenting the results of a placebo test. We restrict the sample to the period 2009-2013 and create a placebo event in 2011 to examine if treatment and control firms engage differently in risk management also in time periods where no relevant oil price decline occurs. In this case a firm is considered as treated if its net worth measured by net income/assets is below the median value of the sample net worth in 2010. Results for the placebo test are displayed in Table 7. The interaction terms are always not statistically significant and also considerably smaller in terms of magnitude compared to the estimates reported in Table 6, pointing to no relevant differences in risk management activities among treated and control companies conditional to their level of net worth.

[21] Smith and Stulz (1985) suggest that direct and indirect cost of bankruptcy should be a key determinant of firms' hedging policies. We do not find evidence to support their prediction with our estimates being more in line with the collateral constraint theory affecting risk management activity; interestingly, our findings still hold even if we exclude distressed firms from the sample.

Table 7
Placebo tests

	Placebo test			
	1	2	3	4
Year>=2010× Treated placebo	-0.001	0.003	-0.001	0.063
	(0.084)	(0.086)	(0.085)	(0.099)
Leverage		0.354		
		(0.267)		
Short term obligations			-0.071	
			(0.378)	
Available Credit lines				0.050
				(0.048)

Difference-in-differences estimates with firm fixed-effects. Robust standard error in parentheses. Dependent variable is 12-month ahead hedging ratio. A firm is considered as treated when its net worth measured by net income/assets is below the median value in 2010. Estimation sample is 2009-2013 for the placebo test. *, **, and *** denote significance at, respectively, the 10%, 5% and 1% level.

6 Optimal hedging strategy and net worth

The previous Sections provided extensive evidence of net worth as a major determinant of firms' hedging decision, an effect amplified when the value of firms' collateral is impaired by severe oil shocks. In this last Section we examine more in detail how optimal hedging strategy and the extensive margin of risk management activities interact with firms' net worth, an aspect often neglected in previous studies on commodity producers.[22] Nevertheless, as shown in Table 3, preferences of firms between linear and nonlinear strategies as well as their choice in terms of specific derivative contracts have evolved over time.

Financial derivatives adopted by E&P firms to hedge oil production differ both with respect to their final payoff structure and in costs, as well as in how they can affect the firms' collateral needs. To the best of our knowledge the only papers specifically devoted to the analysis of the optimal hedging mix in the oil industry are the one by Mnasri et al. (2017b) and Croci et al. (2017). We depart from their approach from several perspectives. First, as previously discussed, we fit our analysis in the framework of dynamic risk management theories, where collateral constraints impinge on the firm ability to engage in derivatives

[22]Several authors presented a theoretical framework for the choice of the hedging strategy see Smith and Stulz (1985), Adler and Detemple (1988), Froot et al. (1993), Brown and Toft (2002), and Adam (2002) among many others.

trading. Hence, we explicitly condition the choice of hedging (the extensive margin) to net worth, as well as to financial constraints. Second, we are the first to examine oil producers hedging strategies in the aftermath of the shale technology. As discussed in Section 1 this transformation not only altered the production from the technological point of view, but also the firms' financial structure via increasing leverage. Moreover, this financial transformation occurred during a period where a severe shock to oil prices particularly stroke small independent E&P producers whose financial hedging could not be replaced by other form of risk management (Kumar and Rabinovitch, 2013).

We focus on the extent of linear hedging measured as oil production covered via linear contracts over total oil production hedged. In this way, we construct an indicator of hedging strategies which is normalized to one, so that the natural complement to linear hedging includes all the remaining oil production hedged via collars, three-way-collars, put options, call options, swaption and other residual contracts. We prefer investigating the extent of linear hedging instead of considering specific nonlinear strategies in the spirit of Adam (2009) for several reasons. First, linear contracts represent a definitely more homogeneous category and their analysis does not require to distinguish among nonlinear contracts with very different payoffs and underpinning strategies.[23] Second, the heterogeneity among nonlinear contracts does not always support a clear-cut identification of the main determinants of the optimal hedging strategy, and the available empirical findings are sometimes inconclusive to this purpose, see Adam (2009) or Croci et al. (2017). Finally, adopting an empirical specification where the dependent variable is split across multiple distinct categories could be problematic for some types of nonlinear derivatives whose use is almost minimal in specific sample years (see Table 3).

We estimate a Heckman model to control for sample selection in the hedging decision.[24] In the first stage, the dependent variable is a binary dummy equal to 1 when the company's 10-K reports derivative contracts in place to hedge oil production. In the second stage, we evaluate the preference for linear hedging by measuring the extent of total notional hedged through linear contracts over the total notional amount of the hedging portfolio; in both stages we include one of our measures of net worth and we control for several variables which have been identified to play a role in shaping risk management strategies. The estimates

[23]For example, a costly short put with no upside cap is typically adopted for insurance purposes, while a three-way-collar may even generate a profit thanks to an additional sold put, but it has no downside protection for very low price levels.

[24]For the sake of brevity the analysis in the previous sections ignored the selection bias for hedging as our main results are not qualitatively affected. Indeed, the significance of the inverse Mill's ratio in the Heckman model is not uniform across net worth measures.

are presented in Table 8, with the selection equation in the bottom panel and the outcome equation in the top panel.

Our selection equation results confirm the evidence on the role of net worth presented in Section 4, also when several controls are included in the specification, with the only exception of the 5 year CDS measure which is still negative but not statistically significant. On the other hand, collateral constraints seem to influence only marginally the decision about the optimal amount of linear contracts. In the outcome equation, a higher net worth is associated with a smaller share of linear hedging, though this result is not uniform and depends on each specific measure. In principle, we acknowledge that a more precise analysis of this result would require detailed information on the extent of collateral absorption by different hedging contracts. Unfortunately, this kind of data is not easy to recover as most of risk management is carried out via OTC contracts with very limited public disclosure. Nevertheless, we believe that some speculations can be made to support these findings. A first one relates to the organizational development of firms, i.e. to the fact that the risk management function could be less developed and skilled in firms with lower net worth, thus explaining their preference for more naive derivative strategies. Alternatively, and probably more interesting in the context of dynamic risk management, linear hedging though being subject to margin calls, does not necessarily require an up-front premium and could be preferred by firms with lower net worth. Conversely, a higher net worth and less tighten financial constraints could explain the use of more complex and expensive nonlinear strategies, which however preserve the upside potential (see also Adam, 2009 on this point).[25]

The impact of the oil price on the decision of whether to hedge is never significant; on the contrary, and not surprisingly, increasing levels of oil production positively affects the probability to enter a derivative contract. Oil price is also found to be strongly positively correlated with the extent of linear hedging. Linear contracts such as swap and forwards allows firms to hedge their production but they do not represent a profitable strategy when oil prices increase because of a cap to the upside potential with respect to nonlinear strategies, a result already documented in Adam (2002) and Adam (2009) for gold mining firms.

Production risk, defined as firm-specific coefficient of variation of oil production, is positively associated with the extent of linear contracts, though this findings is not always confirmed across specifications. Admittedly Brown and Toft (2002) and Gay et al. (2002)

[25]Some anecdotal evidence of this assumption can be recovered from the increasing adoption of 3-way collars starting from 2011 with producers being increasingly confident on the historically high oil prices. Hence, if the use of 3-way collars was originally conceived to realize a better upside exposure, it proved to be a very costly and ineffective hedging strategy after the oil price collapse in 2014-2015.

Table 8
Hedging choice and derivative strategy

	Income/ Asset	Market Cap.	Equity/ Asset	Size	CDS	Default 1 year
			Outcome equation			
Net worth	0.048	-0.038***	0.004	-0.037**	-0.005	0.016**
	(0.072)	(0.012)	(0.170)	(0.015)	(0.007)	(0.006)
Oil price	0.318***	0.350***	0.288***	0.284***	0.381***	0.399***
	(0.101)	(0.097)	(0.096)	(0.096)	(0.109)	(0.104)
Production uncert.	0.128*	0.088	0.128*	0.080	0.299***	0.284***
	(0.071)	(0.073)	(0.074)	(0.073)	(0.087)	(0.086)
Investments	-0.132***	-0.120***	-0.134***	-0.142***	-0.223**	-0.216**
	(0.045)	(0.042)	(0.046)	(0.048)	(0.094)	(0.087)
Profit diversif.	-0.308***	-0.379***	-0.283***	-0.338***	-0.396***	-0.366***
	(0.097)	(0.098)	(0.098)	(0.099)	(0.109)	(0.103)
Leverage	0.212	0.222	0.249	0.262*	0.426**	0.366**
	(0.171)	(0.145)	(0.183)	(0.136)	(0.187)	(0.181)
Leverage^2	0.075	-0.006	0.017	-0.008	-0.039	-0.071
	(0.103)	(0.069)	(0.070)	(0.067)	(0.114)	(0.118)
Stock options	-0.034**	-0.032**	-0.035**	-0.028*	-0.016	-0.011
	(0.015)	(0.015)	(0.015)	(0.015)	(0.019)	(0.020)
Dividends	0.015*	0.032***	0.014	0.027***	0.025***	0.024***
	(0.009)	(0.009)	(0.008)	(0.010)	(0.009)	(0.009)
			Selection equation			
Net worth	0.680***	0.202**	1.972***	0.298**	-0.031	-0.151***
	(0.257)	(0.102)	(0.580)	(0.133)	(0.034)	(0.044)
Oil price	-0.076	0.003	0.136	0.038	0.060	-0.031
	(0.419)	(0.444)	(0.422)	(0.428)	(0.457)	(0.448)
Oil production	8.258**	7.087*	7.503**	5.631	8.140**	7.512*
	(3.792)	(3.787)	(3.767)	(3.442)	(3.841)	(3.883)
Investments	-0.450	-0.527	-0.778*	-0.514	-1.134***	-1.263***
	(0.372)	(0.385)	(0.435)	(0.339)	(0.426)	(0.425)
Profit diversif.	0.921*	1.283**	0.837*	1.023**	0.605	0.469
	(0.475)	(0.583)	(0.506)	(0.493)	(0.535)	(0.477)
Leverage	3.347***	2.947**	3.793***	2.844**	2.015	2.936**
	(1.102)	(1.223)	(1.228)	(1.133)	(1.274)	(1.147)
Leverage^2	-2.717***	-3.266***	-1.814**	-2.557***	-1.764**	-2.120**
	(0.912)	(1.007)	(0.888)	(0.932)	(0.862)	(0.847)
Stock options	0.204*	0.167	0.218*	0.212*	0.172	0.206*
	(0.123)	(0.121)	(0.126)	(0.124)	(0.118)	(0.121)
Dividends	0.178*	0.091	0.217**	0.158	0.155	0.160
	(0.096)	(0.109)	(0.093)	(0.103)	(0.104)	(0.103)

Robust standard error in parentheses. In the selection equation, the dependent variable is equal to 1 when the firm is engaged in risk management activities. In the outcome equation the dependent variable measures the extent of linear notional over total amount of notional hedged. The header of each column indicates the measure of net worth that is used in the estimation, see the text for precise definitions. *Average oil* is the annual average of the WTI oil prices, *Production uncertainty* is the coefficient of variation of firm oil production, *Oil production* is the amount of crude oil produced by the firm in thousands of barrels per day, *Investment* is defined as firm's capital expenditure over net property, plant, and equipment, *Leverage* is Total Debt/Assets, *Profit diversification* is the ratio between revenues from E&P activities and total revenues, *Dividends* are cash dividends in millions, *Stock options* is the amount of stock options granted to firms' executives. Missing values for stock options are replaced with zeros. Firms fixed effect are included in the selection equation. *, **, and *** denote significance at, respectively, the 10%, 5% and 1% level.

show that when firms' risk spectrum widens to include additional non-hedgeable risk such as production uncertainty, this amplifies the degree of non-linearity in the firms' exposure, hence risk managers should increase their exposure to nonlinear contracts, a result which is empirically found also in Mnasri et al. (2017b) but not in Adam (2009).[26]Capital expenditures measuring firms' investment propensity are negatively correlated with risk management activities and with the use of linear contracts. Froot et al. (1993) show that firms with large investment programs should be active hedgers, with the amount of nonlinear contracts increasing in the nonlinearity of capital expenditures. Our estimates do not confirm the first prediction, and underscore again the relevant trade-off, driven by collateral constraints, between hedging and investments. On the contrary, we confirm the second prediction, particularly fitting for E&P companies where investment programs are highly nonlinear and strongly dependent on oil prices. We also find that less diversified firms are more likely to engage in financial hedging, consistent with the absence of other forms of diversification via either natural or operational hedging (Kumar and Rabinovitch, 2013). In addition, our results suggest that a lower industrial diversification is also strongly associated with the use of nonlinear contracts. More diversified firms could be more flexible in halting production with adverse oil market conditions. In turn this translates in their resorting more to nonlinear hedging strategies.

Leverage is found to be a significant determinant of the choice to initiate a derivative strategy[27] a result consistent with the empirical analysis in Haushalter (2000) and with the theoretical prediction in Smith and Stulz (1985) who are first to emphasize the value of risk management as a factor reducing expected costs of bankruptcy. However, our findings point to a more interesting result, with the lower panel of Table 8 showing a clear non linear relationship: more leveraged producers are increasingly likely to hedge, but when closer to default the sign of this relationship changes. As a possible explanation for this result we refer to the so-called option to default: firms facing very high distress costs avoid hedging and divert money to new projects instead of preserving value for bondholders, because of the limited liability condition. Our findings validate the implications of the risk-shifting model of Fehle and Tsyplakov (2005): firms dynamically adjust their positions with respect

[26]The result on production uncertainty should be interpreted with some caution as this variable actually resembles more to a sort of firm fixed-effect rather than a time varying measure of production uncertainty. For the same reason we exclude, after testing for their statistical significance, similar regressors from the empirical specification such as price-quantity correlation or the correlation between oil price and firm cash flows, suggested by Froot et al. (1993), Gay et al. (2002), and Brown and Toft (2002) among others.

[27]Results are qualitatively similar when we substitute leverage with alternative indicators of firms' indebtedness such as the available amount of credit lines.

to both the extent of the hedging activity and the maturity of the hedging position, with the use of risk management displaying a non-monotonic relation with leverage and proximity to financial distress.

In their seminal contributions, Stulz (1984) and Smith and Stulz (1985) characterize hedging in a theoretical framework where managerial risk aversion and incentives are explicitly taken into account. Generally speaking, a risk-averse manager accepts to bear some risk as long as her utility function is convex with respect to the value of the firm; in this case, the manager will be willing to limit the use of hedging and benefit from some volatility in the firm's earning distribution. This could be achieved by designing a convex compensation scheme for the manager, for example by increasing the share of stock options over total executive compensation. In the context of oil and gas companies, Bakke et al. (2016) exploit a change in financial accounting standards as a quasi-natural experiment and find that the decline in managerial risk taking does actually transpose in higher corporate hedging; on the contrary, Croci et al. (2017) do not find empirical support for managerial risk incentives as a driver of the hedging strategy. We proxy the convexity of the managerial compensation scheme via the use of stock options granted to executives; our findings are not able to support the theory as to the choice of entering a derivative contract, while we document a quite robust negative link between the distribution of stock options and the use of linear contracts. We interpret this result as evidence of a managerial preference for strategies that do not cap the upside potential in presence of more convex compensation scheme. Finally, cash dividends exhibit a positive effect on the probability of hedging though the estimates in the selection equation are not always statistically significant. On the contrary, the results in the outcome equation generally indicate an increasing extensive margin achieved through linear contracts for firms with wealthy dividend policies (Adam, 2009).

7 Conclusions

In this paper we used a new hand-collected data set containing detailed information on U.S. oil producers' hedging portfolios. Our study contributes to develop the literature on financial risk management in a sector that has experienced a deep technological (shale revolution) and financial transformation (increasing leverage) over the last decade. Consistently with modern risk management theories, we documented for the first time a strong positive link between net worth and hedging in the oil producing sector. These findings are robust to different model specifications as well as to accounting and market-based measures of net worth. Our results are of particular interest as they are obtained by analyzing firms where the value of collateral assets strongly depends on the risk factor to be hedged, i.e. the oil price. Exploiting the oil price slumps in 2008 and in 2014-2015 as quasi-natural experiments, we also showed how an oil price shock differently affected risk management practices among E&P firms on the basis of their net worth. Interestingly, in the second oil slump we find a significant role of leverage and credit constraints in reducing the hedging activity. We interpreted this result as a sign of the increasing relevance of the debt component in the firms' "collateral call", a fact that we attribute to the marked increase in leverage following the diffusion of the shale oil technologies. Finally, in the last part of this study we examined more in detail how optimal hedging strategy and the extensive margin of risk management activities interact with firms' net worth. In this case the effect is less apparent though it generally points to a more limited use of linear strategies when firms' net worth increases. The motivations driving this last decision could represent a future interesting research question.

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