CEO compensation and corporate risk: Evidence from a natural experiment☆

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Abstract

This paper examines the two-way relationship between managerial compensation and corporate risk by exploiting an unanticipated change in firms' business risks. The natural experiment provides an opportunity to examine two classic questions related to incentives and risk—how boards adjust incentives in response to firms' risk and how these incentives affect managers' risk-taking. We find that, after left-tail risk increases, boards reduce managers' exposure to stock price movements and that less convexity from options-based pay leads to greater risk-reducing activities. Specifically, managers with less convex incentives tend to cut leverage and R&D, stockpile cash, and engage in more diversifying acquisitions.

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1. Introduction

Option-based compensation for corporate executives has grown significantly over the past 30 years. It is commonly believed that stock options provide managers with incentives to take risks, but the evidence remains unclear. Even less is known about how boards of directors design and adjust managers' incentives in light of the firm's risk environment. The lack of definitive findings may seem surprising given that the issue has been studied extensively. However, theoretical predictions are varied and overcoming identification concerns remains challenging. In this paper, we take a new approach to these classic issues in an attempt to augment our understanding of the relationship between risk and incentives.

Providing empirical evidence is important because theory's prediction of how options affect risk-taking incentives is ambiguous. On the one hand, options' convex payoffs create an incentive to take risk because managers share in the gains but not all of the losses. This intuition appears in Jensen and Meckling (1976), Myers (1977), Smith and Stulz (1985), and Smith and Watts (1992).[1] On the other hand, Lambert et al. (1991) show that, because options contain a leveraged position in the firm's equity, options also have the potential to magnify a risk-averse manager's exposure to the firm's risk and thus reduce the manager's appetite for risk.[2]

Despite this theoretical ambiguity, there is a wealth of empirical evidence highlighting a positive correlation between the use of options in pay and various measures of risk, such as stock-return volatility. Work of this nature dates back to Agrawal and Mandelker (1987), if not earlier, and extends to Tchistyi et al. (2011).[3] For example, Guay (1999) shows that it is specifically the convexity of stock options that determines the sensitivity of CEO wealth to equity risk. He finds that firms' stock-return volatility is positively associated with the convexity of the CEO's full compensation package (including previously granted stocks and options), which has come to be known as *vega*.

[1] See also Haugen and Senbet (1981), Bizjak et al. (1993), Gaver and Gaver (1993), and Guay (1999).
[2] Option compensation may also increase or decrease the firm's risk as a by-product of increasing managerial effort (Kadan and Swinkels, 2008). See also Carpenter (2000) and Ross (2004).
[3] Papers documenting a positive association between options and firm risk include DeFusco et al. (1990), Saunders et al. (1990), Mehran (1992, 1995), May (1995), Tufano (1996), Berger et al. (1997), Denis et al. (1997), Esty (1997a, 1997b), Jolls (1998), Schrand and Unal (1998), Aggarwal and Samwick (1999), Guay (1999), and Knopf et al. (2002).

Although this evidence suggests that risk-taking and vega are linked, identifying the causal effect of option-based incentives on corporate risk-taking is difficult given the obvious endogeneity of the relationship between options and risk. Because managers' compensation is arguably designed in anticipation of a particular risk environment, the possibility of reverse causality is hard to exclude. Similar concerns about endogeneity plague the empirical literature on ownership concentration and firm value (Demsetz and Lehn, 1985; Himmelberg et al., 1999; Palia, 2001).

There have been several attempts to solve this identification challenge. A number of papers approach this question by estimating a system of simultaneous equations (see Coles et al., 2006; Rajgopal and Shevlin, 2002; Rogers 2002). Although this approach makes progress by modeling the effects of vega on decisions *and* vice versa, a fundamental concern remains in that the estimations in these papers require arbitrary exclusion restrictions.[4] A similar concern applies to Armstrong and Vashishtha (2010), who attempt to resolve the endogeneity problem using instrumental variables.[5] Other recent work attempts to overcome the challenge by analyzing firms' risk-taking following new accounting rules that reduced options pay (Chava and Purnanandam, 2010; Hayes et al., 2012). These new accounting rules, however, were known and debated for years in advance, undermining their effectiveness as a natural experiment;[6] further, because the rule change affected all firms at the same time, these analyses also lack a compelling counterfactual. In sum, although the estimation strategies in this literature have grown more sophisticated and certainly made progress, important identification concerns remain.

We take a step forward in addressing the identification challenge by exploiting changes in firms' business environments that increase left tail risk (also known as material risk) that can truly be classified as exogenous and unanticipated. Left tail risks are prevalent in practice and can take the form of technological irrelevance, adverse regulatory changes, asset expropriation, and so on. The specific tail

[4] Coles et al. (2006) assume that the riskiness of the firm's business environment does not affect project choice; Rajgopal and Shevlin (2002) assume that cash balances and firm size are unrelated to firms' risk choices; and Rogers (2002) assumes that cash balances and stock variance are unrelated to firms' hedging motives.

[5] Armstrong and Vashishtha (2010) assume that cash balances, marginal tax rates, past stock returns, and past profitability are unrelated to the proportion of firms' overall risk that is systematic.

[6] For example, Aboody et al. (2004) highlight that over one hundred firms voluntarily expensed stock options as early as 2002 in anticipation of the 2005 adoption of FAS 123R, which was studied by Chava and Purnanandam (2010) and Hayes et al. (2012).

risk we study is the risk of large legal liabilities and costly regulation. This setting provides an opening to examine how managers respond to an increase in business risk as a function of their pre-existing equity-based incentives. The unanticipated change in risk allows us to exclude the possibility of reverse causality between these pre-determined incentives and managers' subsequent risk-related choices.

Our empirical analysis centers on a jump in tail risk that is created when a chemical to which a firm's workers have already been exposed is newly identified as a carcinogen. Discovery of a chemical's carcinogenicity increases the likelihood that a firm will need to spend large sums on legal fees, damage payments, and insurance premiums in the future. It also raises the risk of costly future workplace safety regulations. This increased potential for large cash outflows elevates the likelihood of future poor performance and distress, allowing us to cleanly identify an increase in firms' business risks. The workplace exposures also reduce firms' investment opportunities. Unlike a mean-preserving increase in risk, the left-tail risk decreases the firms' expected returns on investments; the risk increases both the expected costs of production and the probability that returns are diverted to cover liability costs.

Gormley and Matsa (2011) confirm that such workplace exposures to carcinogens can reduce investment opportunities and increase a firm's risk of future financial distress. Using data on workplace exposures to known carcinogens, historical damage awards (Pontiff, 2007), and historical cash flows, Gormley and Matsa find that a typical potential legal liability faced by firms appears to be around 5% of assets and that such a shock would increase the median probability of distress among exposed firms by 30-fold. This underestimates the risk, as it does not account for the possibility of adverse future regulatory changes.[7] Consistent with a decline in investment opportunities, Gormley and Matsa also find that shareholders prefer for managers to pay out more cash after the tail risk increases.

Given the drop in investment opportunities, boards have reason to reduce managers' exposure to their firms' risk. With fewer risky, yet worthwhile projects, the boards no longer need to provide risk-averse managers with as much pay convexity (vega) or sensitivity to firm value (known as *delta*) as

[7] An analysis of firms' stock volatility in our sample (discussed later) also suggests that these exposures are salient; the variance of stock returns for firms with an exposure increases by 60% after risk increases.

incentives to undertake risky investments (e.g. Hirshleifer and Suh, 1992; Smith and Watts, 1992). Other factors, discussed in Section 2.1, might also cause boards to decrease stock-based incentives and lead managers to alter their financial exposure to the firm (e.g., by exercising options). While new compensation awards can adjust quickly, managers' overall sensitivities to stock price movements and stock volatility are likely slower to adjust. Vesting schedules restrict the managers' ability to reduce their personal holdings, and it can be costly for firms to modify securities that have already been awarded.

After growth opportunities decrease, we indeed find that boards respond by immediately adjusting compensation flows so as to reduce managers' exposure to their firms' risks. Boards reduce the sensitivities of CEOs' pay to changes in firm value (delta) and to changes in the firm's risk (vega) in the years immediately after the firm is exposed. In this way, the firms appear to actively manage grants of new equity incentives, consistent with Core and Guay (1999). We also find that managers seek to reduce their future exposure by exercising a greater number of stock options just after the carcinogen is discovered. These results underscore concerns about reverse causality in prior studies of CEO incentives' effect on corporate risk-taking.

In contrast to our findings for compensation flows, however, we find that the sensitivity of the manager's overall compensation portfolio to firm risk is harder to modify quickly. We find that it takes three to five years before the vega and delta of the entire compensation portfolio are significantly reduced. That is, although boards react quickly to adjust new incentives in light of the increased risk, these changes take time to shift the sensitivity of incumbent CEOs' total firm-related wealth to firm risk. The opposite is true for new CEOs, for whom the board gets a fresh start in fashioning incentives. Indeed, we find that new CEOs have significantly lower portfolio vegas than do the CEOs they replace at the exposed firms and lower portfolio vegas than do other newly appointed CEOs at unexposed firms.

To identify an effect of convexity on risk-taking behavior, we make use of a previously unexplored effect of convexity on risk-taking incentives. Using a theoretical example in the framework of Lambert et al. (1991), we show that the convexity of CEOs' payoffs affects both the desired level of risk-taking and how sensitive CEOs are to deviations from this level. Unlike the prior literature, we focus on the latter effect of convexity. After an unanticipated increase in risk pushes a risk-averse manager above his desired level of risk taking, the manager can benefit by reducing risk. However, when the manager has a convex payoff, he gains less by reducing risk because the reduction lowers the expected value of the convex payoff. Higher vega thereby provides the manager with the incentive to reduce risk less aggressively.

The unanticipated increase in left-tail risk thus affords us a unique opportunity to identify a causal effect of these incentives on managerial risk-taking. As illustrated by our theoretical framework, the level of convexity immediately after risk increases affects risk-taking incentives in the new environment. Because the manager's compensation portfolio structure prior to the jump in tail risk is highly correlated with their portfolio immediately afterwards, we can use these predetermined incentives to analyze how option-based convexity affects managerial responses to an increase in risk, thereby avoiding concerns about reverse causality.

Focusing on a short window of three years after risk increases and excluding any firm-years after CEO turnover (because the pre-existing portfolio corresponds to a different CEO and is thus less informative in those cases), we find that the convexity of a managers' pre-existing, equity-based incentives is positively related to the increase in their firms' risk after a carcinogen is discovered. On average, exposed firms' stock variance increases by about 0.10 after the jump in tail risk, and exposed firms whose CEOs face high vega see the largest increase in stock variance—a one standard deviation greater vega is associated with a 50% larger increase in the stock variance. This finding suggests that managers with more convex payoffs are less likely to take actions to offset the increase in left tail risk and provides the most definitive evidence to date that the convexity of managerial pay packages directly affects managerial choices with respect to corporate risk.

We also explore the specific financing and investment choices managers make that affect firm risk and find that these choices are also related to managers' portfolios. Gormley and Matsa (2011) find that the average firm responds to a jump in tail risk by reducing leverage and diversifying through acquisitions of cash-rich firms. We explore heterogeneity in these responses. We find that CEOs with high portfolio vegas reduce leverage less than CEOs in other exposed firms. Similarly, we observe significantly less stockpiling of cash by CEOs with higher vegas. Convex payoffs also appear to make CEOs less likely to engage in diversifying acquisitions and less aggressive in cutting back on risky investments, as captured by smaller cuts in their firms' R&D expenses.

Our findings do not appear to be driven by omitted variables, which could be a problem if factors that are correlated with the initial choice of compensation structure also affect how a firm responds to the increase in tail risk for reasons unrelated to compensation. For example, highly risk-averse managers might respond more aggressively to reduce risk after tail risk increases. If firms compensate highly risk-averse managers with *less* option-based pay, then this might explain the observed correlation between convexity and changes in financial and investment decisions. However, theory suggests more risk-averse CEOs will actually be given *more* convex incentives (e.g., Guay, 1999). Our results for vega are also robust to controlling for manager fixed effects and interactions of exposure with various measures that are likely to be correlated with managerial risk tolerance, including corporate financial vulnerability, external governance, and CEO age and tenure.

Taken together, these results suggest that the structure of managerial compensation has important effects on corporate responses to tail risk and that the convex payoffs provided by options do affect risk-taking incentives. In particular, options can increase a firm's overall risk by reducing managers' incentives to undertake risk-reducing activities when facing a jump in left-tail risk. Relative to stock, risk-taking incentives from options' convexity appear to reduce the sensitivity of a manager's expected utility to deviations from the manager's desired level of risk.

Our paper addresses two distinct, but connected, questions regarding managerial compensation and risk: how do convex payoffs affect managers' risk-taking incentives and how do firms' risky investment opportunities affect boards' choices regarding stock-based pay? The interconnectedness of these questions also makes it challenging to answer the second question. Identifying how boards adjust pay is difficult given the lack of exogenous changes in firms' risky investment opportunities. As a result, prior research typically relies on market-to-book ratios as a measure of growth opportunities (e.g. Smith and Watts, 1992; Core and Gauy, 1999) or on regulatory changes that affect managers' incentives to invest in risky projects (Cohen, Dey, and Lys, forthcoming). Our paper takes a new approach by analyzing an exogenous increase in tail risk that directly affects firms' investment opportunities.

The remainder of the paper is organized as follows. Section 2 discusses how managers' portfolios respond to tail risk and illustrates how shocks to tail risk can be used to identify options' effect on managerial risk-taking. Section 3 discusses our empirical setting, data sources, and identification strategy. Section 4 analyzes how boards adjust equity-based incentives in response to an unanticipated change in tail risk. Section 5 examines the managers' responses to increased risk as a function of their existing compensation contract. Section 6 concludes with a discussion of the broader implications of our work.

2. Theoretical framework

This paper exploits a novel way to identify options' effect on managerial risk-taking incentives using unanticipated shocks to business risk. In this section, we discuss how managers' portfolios respond to changes in risk, and why these responses pose an identification challenge to many estimates in the existing literature. We then show how an unanticipated increase in risk can be used to overcome this identification challenge.

2.1. How managers' portfolios respond to left-tail risk

The riskiness of firms' investment opportunities is widely thought to be an important determinant of managers' compensation. Firms often face investment opportunities that have positive net present value but feature significant idiosyncratic risk. Because risk-averse managers may be reluctant to take such risky projects, boards can use convex payoffs to induce managers to do so (e.g., Hirshleifer and Suh 1992; Dittmann and Yu 2011; Edmans and Gabaix 2011). This motive for providing convexity is strongest for firms with many risky investment opportunities, such as growth options (Guay 1999), and thus would lead to a positive association between convexity and firm risk.

In our empirical analysis, we examine how managers' portfolios respond to the increase of a particular type of risk, left-tail risk. Unlike a mean-preserving increase in risk, which maintains the net present value of existing projects, an increase in left-tail risk decreases the expected return by boosting the probability of a very negative outcome. The left-tail risk reduces the chance that shareholders will realize a return on the firm's future investments and affects the manager personally through any undiversified wealth that is tied to the value of the firm. As such, a left-tail risk will likely lead both the board and managers to adjust the portfolio vega and portfolio delta.

Boards have reason to decrease managers' portfolio vega and portfolio delta after left-tail risk increases. By reducing the expected returns on investment, the left-tail risk renders marginal projects economically unviable, thereby reducing the need to provide a risk-averse manager with an incentive to undertake risky investments.[8] In this scenario, boards have reason to reduce managers' compensation vega. The decrease in growth opportunities also reduces the need for delta (Smith and Watts 1992), as do other factors. Risk-averse executives may require a greater premium for holding stock-based pay, leading firms to shift compensation to other forms. Reducing managers' exposure to firm risk, by reducing their stock-based pay, can also mitigate agency conflicts arising from managers' risk aversion (Jensen and Meckling 1976; Amihud and Lev 1981; Holmström 1999), which are particularly acute in the presence of left-tail risk (Gormley and Matsa 2011).

Managers also have a personal incentive to limit their financial exposure to their firms' risk. Left-tail events, such as bankruptcy and employment loss, can lead to severe personal losses, including the loss of private benefits, reputation, and wealth tied to the firm. The most direct way managers can limit their exposure to these risks is to alter their financial portfolio (e.g., by exercising options or selling unrestricted stock).[9] This may lower both vega and delta. Absent that, managers can also modify the firms' risk directly by altering corporate investment (Gormley and Matsa 2011).

These effects of risk highlight the endogenous nature of the managers' compensation contracts. Because firms' risk environment affects the structure of managers' contracts, it is difficult to identify the causal effect of option-based pay on risk-taking incentives by comparing measures of risk-taking to

[8] Indeed, Gormley and Matsa (2010) find evidence that shareholders prefer managers to pay out the excess cash through dividends and stock repurchases following the increase in tail risk described in Section 3.
[9] To the extent that CEOs influence their own pay, they might also shift their compensation away from stocks and options.

managers' portfolio vega and delta. As we describe next, unanticipated shocks to tail risk can be used to overcome this identification challenge.

2.2. Identification based on shocks to business risk

To illustrate how we identify the effect of convex payoffs on risk-taking, we derive the expected utility and marginal expected utility with respect to risk for a manager with different portfolios. Following Lambert et al. (1991), we model a portfolio as a combination of cash, stock, and options that provides a risky payoff, *Z(P)*, at the end of the period, and this payoff is a function of the firm's stock price, *P*. This portfolio can be thought of as the combination of both past and current compensation paid to the manager by the firm's shareholders, along with the manager's outside wealth (including cash, real estate, or other investments), which is not tied to the firm's performance. The stock price *P* is assumed to be a random variable with cumulative probability distribution *F(P)* and density function *f*(*P*), and is bounded below by zero. Letting *U*(*x*) represent the manager's utility when his or her total payoff is *x*, the manager's expected utility can be expressed as

$$\int_0^\infty U\big(Z(P)\big)f(P)dP. \tag{1}$$

In this framework, we analyze a manager's expected utility under different portfolios of stocks and options. We assume the manager has a power utility function with a coefficient of relative risk aversion of two. Similar to the Black-Scholes model, we assume that the firm's stock process follows a lognormal return process, and following Lambert et al. (1991), we assume an initial stock price of $50, annual expected return of 0.10 per year, and an annual variance of returns σ^2.

For simplicity, we analyze the manager's expected utility under two possible portfolios: one with only options and the other with only stock. Similar to Lambert et al. (1991), the options portfolio contains 10,000 options with an at-the-money exercise price of $50. The options are assumed to expire in seven years.[10] The stock portfolio contains 8,255 shares of stock. In both cases, the manager also has $10

[10] The seven-year horizon is chosen to roughly correspond to the average time to expiration for a manager's existing portfolio of options. The differential effect of the options and stock that we show below is also present when using a ten-year horizon, as in Lambert et al. (1991).

million in outside wealth. We chose the particular number of shares in the stock portfolio such that the two portfolios provide the manager with the same expected utility when at the risk level that maximizes expected utility, which is akin to ensuring that the manager's participation constraint is satisfied equally by the two portfolios. We use a positive affine transformation to rescale the utility functions so that this maximum utility is equal to ten. Figure 1 plots the manager's expected utility as a function of stock return variance under the two different portfolios.

The two expected utility functions in Figure 1 illustrate how options' convex payoffs (vega) can influence the manager's optimal level of risk-taking. As shown in Figure 1, the level of stock variance that maximizes a manager's expected utility depends on the manager's portfolio; the optimal stock variance for the manager with the options portfolio is greater than it is with the stock portfolio. The manager's optimal stock variance is chosen to balance incentives from his payoff's convexity and his risk aversion. For a given increase in risk, the increased value of a convex portfolio increases the manager's expected utility, but risk aversion reduces it. At low levels of risk, the gains in expected utility from the portfolio's convexity exceed the losses from risk aversion, providing a net incentive for the manager to take on greater risk. The prior literature has focused on this relationship between the amount of convexity in the payoff structure (vega) and the desired level of risk-taking.[11]

A portfolio's convexity also affects the "risk-curvature" of the managers' expected utility, where risk-curvature is defined as the manager's marginal utility with respect to risk. For example, note the risk-curvature of the managers' expected utility around the optimal levels of risk in Figure 1; the expected utility of the manager with options is flatter around the peak than that of the manager with stock. The difference in risk-curvature arises from the convexity-risk aversion tradeoff. An increase in volatility reduces a manager's expected utility because the manager is risk averse, but convex compensation mitigates this reduction in expected utility because the convexity boosts the expected value of the

[11] Although the option-only portfolio increases risk-taking incentives in this example, this need not always be the case. As shown by Lambert et al. (1991), Carpenter (2000), and Ross (2004), options—particularly those deep in-the-money—also make a manager's wealth sensitive to stock price movements (i.e., options also increase delta), which can reduce risk-taking incentives.

compensation as volatility increases. The same intuition holds in reverse for reductions in volatility; a manager with more convex payoffs experiences smaller changes in expected utility when risk decreases.[12]

Our paper uses this connection between payoff convexity and risk-curvature to design an empirical test that links managers' compensation convexity to risk-taking. Rather than examine the relationship between convexity (vega) and the *level* of risk-taking directly, as in the prior empirical literature, our identification strategy instead examines the relationship between convexity and the *change* in risk-taking after firms' risk unexpectedly increases. Put in terms of the manager's expected utility as a function of risk (Figure 1), we relate risk-taking behavior to convexity-driven differences in risk-curvature at the peak rather than to convexity-driven differences in the location of the peak. Our thought experiment is as follows: assume that a manager has already chosen the level of risk that maximizes his expected utility given the current compensation arrangement; what happens when the firm's risk environment unexpectedly changes?

Observe that when the risk environment changes, the convexity of the manager's potential payoffs also changes. In Figure 2, we plot the vega for each portfolio after risk changes, where vega is measured as the sensitivity of the value of the managers' options to stock price volatility (following Core and Guay, 2002). To match our empirical setting, we model this change in risk as an increase in left tail risk. (The analysis is similar when the increase in stock return variance is mean-preserving; see Appendix B). Specifically, we examine an increase in the probability of a stock price realization below \$10; we plot the effect of increases in this probability of between zero and five percentage points. A five percentage point increase in the probability of a price below \$10 roughly represents a doubling of that probability.[13] Our analysis is robust to varying the size of the shock in both scope (the price below which realization probabilities increase) and scale (the size of the probability increase). As shown in Figure 2, the vega of

[12] Like the effect of options on a manager's desired level of risk, the effect of options on a manager's sensitivity to deviations in risk is also theoretically ambiguous because options provide exposure to stock price movements (i.e., delta) in addition to convexity. In our example, the convexity effect dominates.

[13] An increase in left-tail risk also reduces a firm's overall value and stock price. In this example, a five percentage point increase in the probability of a price below \$10 reduces the firm's stock price by about 5.25%.

the option portfolio declines after left-tail risk increases, while the vega of the stock portfolio remains at zero.[14]

This change in vega, however, does not fully capture the change in risk-taking incentives. Figure 3 plots the manager's marginal expected utility with respect to volatility after left-tail risk increases. Marginal expected utility is plotted separately for the stock and option portfolios. The manager's marginal expected utility is negative for both portfolios but is *smaller* in magnitude for the more convex portfolio. In other words, the convex portfolio provides the manager with *less* incentive to reduce the firm's stock price volatility after risk increases even though its vega declines by more. This difference in incentives relates to the risk-curvature of expected utility around its peak and the underlying convexity-risk aversion tradeoff. A risk-averse manager, irrespective of his portfolio, gains from reducing risk, but this gain is less when reducing risk also reduces the expected value of convex payoffs. If it is costly or simply difficult to adjust the firm's risk, this effect of convexity makes the manager less responsive to the firm's changing risk environment.

As illustrated by Figures 2 and 3, after risk increases, risk-taking incentives are associated with the degree of payoff convexity, not the change in that convexity. Our empirical tests, therefore, relate managers' responses to their pay structure. We measure their pay structure immediately prior to risk unexpectedly increasing because these incentives are predetermined and highly correlated with their incentives *immediately* afterwards, which we do not observe directly. The ex post vega and delta that we do observe are also affected by managers' endogenous responses, including adjustments to financial leverage, cash holdings, R&D, and acquisitions. By affecting firm risk, these managerial actions also affect the convexity of managers' own payoff structure, thereby making it difficult to identify the direction of causality when relating managers' actions to the *ex post* level of convexity.

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[14] Theoretically, the effect of an increase in left-tail risk on the convexity of the payoff structure is ambiguous. The partial derivatives of vega with respect to volatility and stock price can be positive or negative depending on other parameters. In our example (and in our empirical findings), left-tail risk reduces vega. Strictly speaking, the stock portfolio's convexity is also affected by the increase in tail risk, but the effect is small and not picked up by our definition of vega (see Guay 1999 and Core and Guay 2002).

By focusing on how vega is related to *responses* to unanticipated increases in risk, rather than absolute levels of risk-taking, our empirical approach allows us to avoid the concerns about reverse causality that plague the existing literature. Traditionally, researchers have compared the vega of managers' portfolios to measures of firm risk, but as shown in Section 4, the firms' risk environment influences boards' choices regarding managers' equity-based pay. Absent exogenous shocks to managers' option-based incentives, this reverse causality is a difficult identification challenge for the traditional approach to overcome. Because our approach focuses instead on how vega affects responses to increased risk, avoiding concerns about reverse causality only requires that the increase in risk be unanticipated.

Thus, our approach to identify convexity's effect on risk-taking requires three assumptions:

1) The increase in left-tail risk is unanticipated.
2) The portfolio vega (portfolio delta) immediately prior to risk increasing is positively correlated with the portfolio vega (portfolio delta) immediately afterward.
3) The portfolio vega and portfolio delta immediately prior to risk increasing are not correlated with variables that also affect companies' responses to the increased risk.

The first assumption enables us to rule out reverse causality. The second assumption allows us to use the ex ante portfolio vega and portfolio delta as proxies for the *unobserved* ex post portfolio vega and portfolio delta that drive risk-taking incentives. And the third assumption pertains to omitted variables. Unlike the traditional empirical approach, which must assume the absence of unobservable factors that affect both managers' portfolios and firms' risk, our assumption is narrower. In order for an unobserved variable to be problematic in our setting, it must affect both managers' portfolios and how firms respond to unanticipated changes in risk. We evaluate and rule out potential confounders in robustness tests reported in Section 5.

3. Empirical setting

In this paper, we analyze left tail risk that is created when a chemical to which a firm's workers have already been exposed is newly identified as a carcinogen. The discovery increases both the liability and regulatory risks of the firm. Using data on workplace exposures to known carcinogens, historical damage awards, and historical cash flows, Gormley and Matsa (2011) find that a typical legal liability faced by firms with such workplace exposures is around 5% of assets, and that such a shock would increase the median probability of distress among exposed firms by 30-fold. The possibility that future regulation might limit the use of these chemicals and significantly increase a firm's cost of doing business further increases the risk of future distress. See Gormley and Matsa (2011) for a more detailed description of the liability and regulatory risks associated with workplace exposures and why firms cannot easily insure or protect themselves from these risks.

Identifying workers' exposure to newly identified carcinogens requires the combination of information on (1) scientific discoveries related to chemical carcinogenicity and (2) which firms use these chemicals. Following Gormley and Matsa (2011), we use the National Toxicology Program's (NTP) *Report on Carcinogens* (*RoC*) for information about the timing of discoveries and the National Occupational Exposure Survey (NOES) to identify firms in which workers were likely to have been exposed to these chemicals. We considered various other data sources, including International Agency for Research on Cancer monographs, California Proposition 65, and the Environmental Protection Agency's Integrated Risk Information System. We chose to rely on the *RoC* because each edition is comprehensive, because it provides a long time series, and because U.S. law requires firms to monitor the list. For example, firms are required to warn employees about their exposure to substances that are included in the *RoC* [U.S. Government Regulation 29 CFR, parts 1910.1200(b)(1) and (d)(4)]. Although the *RoC* is not updated annually, Gormley and Matsa (2011) find that firms do not respond until only *after* chemicals are added to the list.

We determine whether a firm is affected by the listing of a newly classified carcinogen based on the firm's SIC code in Compustat in the year prior to each new listing.[15] We consider a firm to be affected if it operates in a 4-digit SIC code in which at least 5% of workers were observed to be exposed to the

[15] To accomplish this, we first convert the NOES data, which are reported using the SIC-1972 coding scheme, to the SIC-1987 coding scheme used by Compustat, by applying an employee-weighted concordance table from the Bureau of Labor Statistics (1989). We then determine which firms were affected by an increase in tail risk based on Compustat's historical measure of a firm's industrial classification.

carcinogen in the NOES. The 5% cutoff captures 32 unique chemical additions to the *RoC* after 1983 and roughly the top third of observed exposures at the industry level, corresponding to the discoveries that are most likely to result in increased legal liability and future distress.[16]

Our data on firms' financials are from Compustat, and our data on executive compensation are from Yermack (1995) and Execucomp. Yermack (1995) covers the approximately 800 firms listed by *Forbes* magazine as among the largest 500 largest U.S. public corporations in the years 1984–1991, and Execucomp covers about 3,000 S&P 1,500 firms in the years 1992–2008. Our main CEO incentive measures are the sensitivity of the CEO's firm-related wealth to stock price movements and its sensitivity to stock price volatility. We calculate a manager's sensitivity to stock price movements from his or her portfolio of stock and options using the Core and Guay (2002) definition—the dollar change in wealth experienced by the manager for a 1% increase in the firm's stock price. This sensitivity measure is commonly referred to as the "delta" of a manager's portfolio. We calculate the sensitivity to stock price volatility using the dollar change in wealth experienced by the manager for a 0.01 increase in the volatility of a firm's stock price. This measure of sensitivity is commonly referred to as the "vega" of a manager's portfolio and has been used to measure a manager's incentive to take risks (e.g., Guay, 1999; Habib and Ljungqvist, 2005). Both incentive measures are expressed in thousands of dollars. Details on the construction of all variables are in Appendix A.

To ensure a consistent sample of observations across specifications, we exclude observations with missing values for the inputs necessary to calculate the manager's delta and vega in the year prior to a chemical being added to the *RoC*. In all, 143 firms with both financial and compensation data are affected by a newly identified carcinogen, and these increases in tail risk occur for different firms in 1985, 1989, 1991, 2000, and 2004. These firms operate in 43 different 4-digit SIC industries and span 21 of the 48 Fama and French (1997) industries. (Fama-French industries are collections of 4-digit SIC industries that are meant to represent broader industry categories.)

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[16] We use a lower cutoff than do Gormley and Matsa (2011) because of the relatively small number of exposed firms for which compensation data are available.

For each new chemical listing in the RoC, we construct a comparison group of unaffected firms (firms without observed exposures to any newly listed carcinogens) that were present in the same Fama-French industry classification as one of the affected firms. To ensure an adequate control sample in each industry, we drop both affected and unaffected observations in Fama-French industries in which there is not at least one unaffected firm for every ten affected firms. (Our findings are robust to using other exclusion thresholds.) This yields a comparison sample of 341 unexposed firms in 82 SIC industries.

Firms with exposures to the newly identified carcinogens are strikingly similar to our sample of unexposed firms before the listing of a new carcinogen. Ex ante characteristics of firms with exposures are reported in column (1) of Table 1, and the ex ante characteristics of firms without exposures are reported in column (2). Even though we match firms based only on Fama-French industries, the two groups are similar in average stock variance, size, market-to-book, and profitability. Annual compensation and equity-based incentives, as measured by log total pay and the fraction of pay given as options, are also similar across the two groups of firms. The differences in delta and vega of managers' full portfolio of options and stocks are less than one-tenth and one-eighth of a standard deviation, respectively.[17] As shown by the *p*-values reported in column (3), we are unable to reject the null hypothesis that exposed and unexposed firms are similar in all of these dimensions before risk increases.

As in Gormley and Matsa (2011), the use of the NOES likely introduces a degree of measurement error in our ability to identify firms with potential exposures, possibly leading us to underestimate the true effect of tail risk. There are two main measurement issues. First, the NOES only provides data on exposures at the 4-digit industry level; firm-level data is not available. Our subsequent analysis implicitly assumes that all firms in the industry are affected and calculates the average effect. If not all firms in the industry are affected, then we are underestimating the true average effect of the increase in tail risk. Second, firms may have stopped using a dangerous chemical after the NOES was completed in 1983 but before the chemical's listing in the *RoC*. Whereas firms would still be liable for past exposures, the increase in liability risk would be smaller in such cases. Despite these measurement concerns, Gormley

[17] The standard deviations of portfolio delta and portfolio vega are 2,179 and 120.8, respectively.

and Matsa (2011) present evidence to suggest that the NOES indeed captures exposures that later become significant liability and regulatory risks.

An analysis of firms' stock volatility suggests that the liability and regulatory risks associated with these exposures are salient. Figure 4 plots the annualized daily variance of exposed and unexposed firms' stock returns, relative to the year before a new chemical is added to the *RoC*. Whereas exposed and unexposed firms' stock variances track each other quite closely before the carcinogen comes to light, they diverge sharply afterward with stock variance increasing by about 60% among exposed firms. The sharp change in volatility after a chemical is added to the *RoC* confirms that new *RoC* listings correctly capture the timing of increases in business risk.

Gormley and Matsa (2011) analyze corporate responses to this increase in risk. They find that firms, especially those with weak balance sheets, tend to respond to such risks by acquiring large, unrelated businesses with relatively high operating cash flows. The diversifying growth is primarily funded with equity, thereby reducing overall financial leverage, and appears to be motivated primarily by managers' *personal* exposure to their firms' risk in that the growth has negative announcement returns and is related to firms' external governance, institutional ownership, and inside ownership, as measured using the share of the firm's stock held by the firm's management team. The analysis here directly examines the role of CEOs' compensation, its convexity, and its effect on risk-taking incentives. In particular, we examine how quickly boards change the structure of CEOs' compensation to reflect the new risk environment, and we exploit CEOs' pre-existing stock and options holdings (that were awarded before the manifestation of the tail risk) to analyze whether the convexity of managers' payoff structure is related to risk-taking incentives.

4. How business risk affects the structure of managerial compensation

To examine how compensation structures respond to increased tail risk, we compare changes in the exposed and unexposed firms' managers' compensation structures around the time that a new carcinogen is listed in the *RoC*. For each year that new carcinogens are listed, we construct a cohort of exposed and unexposed firms using firm-year observations for the three years before and the three years after the listing. We start with three-year windows to examine how compensation changes in the immediate aftermath of the increase in tail risk. Firms are not required to be in the sample for the full six years around the listing. We then pool the data across cohorts (i.e., across all new carcinogen listings) and estimate the average treatment effect. Specifically, we estimate the following firm-panel regression:

$$Incentives_{ijct} = \beta_0 + \beta_1 Exposure_{jct} + \omega_{tc} + \gamma_{ic} + \varepsilon_{ijct}, \quad (2)$$

where $Incentives_{ijct}$ is one of several dependent variables of interest related to the structure of the chief executive's compensation for firm *i* in year *t*, and *Exposure* is an indicator that equals one if at least 5% of employees in cohort *c* and industry *j* were observed to be exposed in the NOES to a known *RoC*-listed carcinogen as of year *t*. For an exposed firm, this indicator changes from 0 to 1 when the chemical is identified as a carcinogen. We include firm-cohort fixed effects, γ_{ic}, to ensure that we estimate the impact of exposure after controlling for any fixed differences between firms; we include year-cohort fixed effects, ω_{tc}, as a non-parametric control for any secular time trends. We allow the firm and year fixed effects to vary by cohort because this approach is more conservative than including simple fixed effects. In our baseline specification, we deliberately do not control for any time-varying accounting variables because these variables are likely to be affected by the increase in tail risk, and their inclusion could thus confound estimates of β_1.[18] In any event, the inclusion of standard controls, as we report in each table, does not qualitatively affect the results. To account for potential covariance among firm outcomes within the same 4-digit SIC code and over time, we adjust the standard errors for clustering at the industry level.

After tail risk increases, there are two primary ways for a manager's financial exposure to the firms' stock price and volatility to change—changes initiated by the company's board and changes initiated by the manager. First, the board can modify the stock and options components of the manager's

[18] Because the increase in tail risk is exogenous, β_1 in Eq. (2) measures the change in the dependent variable caused by the increased tail risk. If we include endogenous controls, then β_1 would instead measure only the portion of the change in the dependent variable caused by the tail risk that is not driven by causal changes in the other controls. For example, suppose the tail risk leads firms to reduce equity risk by decreasing leverage; then a regression of equity risk on the exposure indicator and leverage might yield a coefficient on the exposure indicator that is close to zero—even when exposure causes a substantial reduction in equity risk.

current pay. We measure these adjustments using the vega and delta of managers' *current* year compensation and refer to these sensitivities as "flow vega" and "flow delta" for short. Second, the manager can modify his or her exposure by exercising vested options and/or selling unrestricted stock. We examine both types of changes in Table 2.

We find that boards do in fact modify the incentive structure of managers' annual compensation after tail risk increases. Specifically, they reduce the annual compensation's sensitivities to both return volatility and price. Controlling only for firm-cohort and year-cohort fixed effects, the CEOs' flow vega decreases, on average, by $7,600 per 0.01 increase in the firm's stock return volatility (column 1; $p < 0.05$), and the flow delta decreases by about $12,900 per 1% increase in equity value (column 4; $p < 0.01$). The declines in flow vega and flow delta are robust to additional controls for firm size, CEO tenure, and the CEO's total cash compensation (columns 2 and 5).[19] These decreases are also not driven by CEO turnover; significant drops in both flow incentives remain after excluding ex post observations from both the affected and comparison samples for which a different CEO is in control than in the year before the listing (columns 3 and 6).

The declines in vega and delta are consistent with boards responding to the decline in risky investment opportunities. Because the increase in left-tail risk reduces the expected return on many risky investments, boards have reason to use less convex payoffs and fewer stock-based incentives. The declines could also reflect other considerations, as discussed in Section 2.1.[20]

Managers of exposed firms also take actions to directly reduce their own financial exposure to their firms' risk. In the three years after tail risk increases, CEOs of exposed firms sharply increase the value of options they exercise relative to CEOs of unexposed firms by more than $1 million, after

[19] Our control variables in this and later specifications follow Hayes et al. (2012). All of the variables are defined in Appendix A.

[20] Some caution is warranted before interpreting the decline in convexity after risk increases as evidence that boards in our sample want CEOs to engage in risk-reducing activities, like diversifying acquisitions, rather than just to curtail future investments. Further analysis finds that the reduction in vega is greater among managers with an above-median vega. Even after the reductions, these managers' average vega remains higher than that of other exposed firms and discourages these managers from engaging in the value-destroying, risk-reducing activity documented in Gormley and Matsa (2011).

controlling for size, tenure, and cash compensation (column 8; $p < 0.01$). The increase in the value of options exercised is robust to excluding observations for which a different CEO is present than in the year before the *RoC* listing (column 9). In unreported results, we also find a decrease in the number of shares owned by managers of exposed firms of about 30,000, suggesting these managers may be selling shares in addition to exercising options, but the estimate is noisy and not statistically significant (the standard error is about 85,000 shares).

The timing of these changes coincides with the increase in tail risk. Figure 5 plots point estimates from a modified version of Eq. (2), where we allow the effect of *Exposure* to vary by year from three years before risk increases until three years afterward.[21] The relative changes in flow vega (flow delta) are in the top (middle) panel. There is no indication of a decrease in flow vega or flow delta prior to the increase in tail risk, but afterward, firms with exposure to a newly identified carcinogen tend to reduce their CEO's flow vega and flow delta relative to other firms. These reductions begin the year risk increases and stay lower thereafter.

The timing of the increase in options exercised by managers at exposed firms, presented in the bottom panel of Figure 5, is striking as well. The value of options exercised is practically flat in the years before tail risk increases; before the chemical is added to the *RoC*, managers of exposed firms appear no more likely than do managers of other firms to increase or decrease the number of options exercised. Then as soon as risk increases, managers of firms with exposure to a newly identified carcinogen start exercising options more than do other managers. These managers exercise an additional \$2 million in options relative to managers of similar unexposed firms in the year that risk increases and exercise an additional \$1 million the following year.

The precise timing of these exercise decisions and the changes in flow vega and flow delta suggest that they are in fact *caused* by the increase in tail risk, rather than by any omitted characteristic related to the manager, firm, or industry. The timing of these changes also confirms that firms and their

[21] This analysis examines a longer panel of five years before *Exposure*. The point estimates reported in Figure 5 are estimated relative to the excluded years $T - 4$ and $T - 5$.

managers did not anticipate the chemicals' addition to the *RoC*; if anticipated, we would expect the incentive changes and option exercising to begin prior to the chemical being added to the *RoC*.

These findings highlight the potential for reverse causality in prior studies of CEO incentives and their effect on corporate risk-taking. A firm's choice to use stock- and option-based incentives depends on its risk environment, so a correlation between equity-based incentives and firm risk may reflect the effect of the firm's risk environment on its choice of incentives or vice versa. This joint determinedness of incentives and a firm's risk raises concerns about previous identification strategies that implicitly or explicitly assume the firm's risk environment has no effect on the choice of incentives.

We next analyze the long run changes in the vega and delta of managers' accumulated compensation portfolios—what we call the "portfolio vega" and the "portfolio delta." Table 3 presents results from regressions examining the overall change in portfolio vega and portfolio delta in the years after risk increases. Specifically, we estimate the following firm-level regression:

$$Incentives_{ijc[t=T+k]} - Incentives_{ijc[t=T-1]} = \gamma_1 Exposure_{jc[t=T+k]} + \delta_c + \varepsilon_{ijc}, \qquad (3)$$

where $Incentives_{ijc[t=T+k]} - Incentives_{ijc[t=T-1]}$ is the change in portfolio vega or portfolio delta from the year before a chemical is added to the *RoC* (i.e., $t = T - 1$) to k years after the chemical is added ($t = T + k$) for the CEO of firm i in industry j and cohort c; $Exposure_{jc[t=T+k]}$ is defined as before; and δ_c is a cohort (or, equivalently, year) fixed effect. To focus on how the shift in flow vega, flow delta, and exercising activity affect the portfolio vega and portfolio delta of the existing CEO, we exclude observations in which the CEO in year $T + k$ was not in office in year $T - 1$. We analyze the change in portfolios for newly appointed CEOs below. The standard errors are again adjusted for clustering at the industry level.

We find that the changes in the composition of new compensation awards and in managers' exercising behavior seem to lower CEOs' portfolio vega or portfolio delta three years after tail risk increases, but the declines are not statistically significant. Our point estimate for the three-year decrease in portfolio vega is about \$25,000 per 0.01 increase in a firm's stock volatility, which is about one-fifth of a standard deviation (Table 3, column 1). The three-year decrease in portfolio delta is about \$180,000 per 1% increase in equity value, or about one-fourth of a standard deviation, for managers of exposed firms relative to other managers and relative to their own deltas before risk increases.

Decomposing the exposed firms' vega after risk increases illustrates the sources of these changes and the relative importance of already-granted stocks and options. CEOs' portfolio vega after tail risk increases can be written as the combination of three components:

$$vega_{i,T+k} = vega_{i,T+k}^{pre} + vega_{i,T+k}^{flow} - vega_{i,T+k}^{exercised} . \tag{4}$$

where $vega_{i,T+k}^{pre}$ is the vega in year $T + k$ of the compensation portfolio held by the CEO in year $T - 1$, $vega_{i,T+k}^{flow}$ is the vega of options accumulated through the CEOs' annual compensation flows between years T and $T + k$, and $vega_{i,T+k}^{exercised}$ is the vega of options exercised by the CEO between years T and $T + k$. To estimate how much each of these sources contribute to the changes in vega, we restrict attention to the Execucomp sample, due to data availability. Further details on these calculations are in Appendix C.

We find some evidence of exposed CEOs' portfolio vega decreasing after risk increases, similar to our findings in the full sample. Figure 6, Panel A plots the average portfolio vegas for managers of exposed and unexposed firms. While there appears to be no change in portfolio vega among unexposed firms over the period, the exposed firms' portfolio vega drops in the year that tail risk increases and continues to decrease in subsequent years. The cumulative decline in year $T + 2$ is about one-third of a standard deviation, but similar to the full sample (reported in Table 3, Column 1), it is not statistically significant at conventional levels ($p = 0.15$).

The breakdown of the portfolio vega into its three components reveals the importance of managers' pre-existing portfolio after tail risk increases. As shown in Panel B of Figure 6, the pre-existing portfolio still accounts for almost half of exposed CEOs' portfolio vega three years after the tail risk increases. The continued importance of the pre-existing portfolio may not be surprising in that vesting schedules restrict the changes available to a manager and because it is arguably costly for firms to modify securities that have already been awarded. The ongoing influence of the pre-existing portfolio suggests that the decline in flow vega and flow delta take time to significantly affect the portfolio vega and portfolio delta.

The breakdown shown in Figure 6, Panel B, however, does not allow us to ascertain what proportion of the average drop in portfolio vega is driven by each of the three components. For example, does the pre-existing portfolio vega decline at a greater rate or do vega flows accumulate more slowly? To answer this question, we construct a counterfactual of what the three components would have been absent the increase in risk. The counterfactual assumes that managers exercise the same number of options as in year $T-1$ and that the pre-existing portfolio vega and the flow vega change at the same rate as for unexposed firms.

Relative to this counterfactual, we find that the newly granted compensation's lower vega increasingly contributes to the average decline in vega over time. The estimates are displayed in Figure 6, Panel C. We attribute about a third of the observed drop in CEOs' portfolio vega three years after the increase in left-tail risk to the decline CEOs' pre-existing portfolio vega, about 60% to the reduction in annual flows, and about 6% to increased options exercising.[22] The relative contribution of each source varies over time. In the first year, more than half of the decline in portfolio vega is from the CEOs' pre-existing portfolio, while only about one-third is from the flow vega and 10% is from increased exercising.

This diminishing role of the pre-existing portfolio suggests that the reduced flow vega and flow delta have greater impacts over time. Table 3 reports longer-term changes in portfolio vega and portfolio delta. We find a statistically significant decline in managers' portfolio delta beginning in year four. In the fourth year after tail risk increases, the portfolio delta is about \$350,000 per 1% increase in equity value lower for managers of exposed firms relative to other managers and relative to their own deltas before risk increases (column 4; $p < 0.05$). This decline is about half of a standard deviation in exposed firms' portfolio delta. By the fifth year, portfolio delta decreases by about \$450,000 per 1% increase in equity value (column 6; $p < 0.10$). Beginning in the sixth year after tail risk increases, we also find a statistically significant decline in portfolio vega. The six-year change in portfolio vega is about \$55,000 per 0.01

[22] The positive contribution of the existing portfolio to the decline in vega indicates that, on average, the increase in stock volatility and decrease in stock price caused by the increase in left-tail risk cause a drop in the portfolio vega of exposed CEOs relative to the drop observed for unexposed CEOs. This is consistent with the decline in vega observed in the theoretical example for a CEO with options (see Figure 2). While not presented in Figure 6, we also find that the increase in left-tail risk reduces the average delta of CEOs' pre-existing portfolios.

increase in a firm's stock volatility, which is about 40% of a standard deviation for exposed firms (column 7; $p < 0.10$).

If a manager's existing portfolio is the impediment to portfolio incentives adjusting quickly, then one would expect portfolio incentives for new CEOs to exhibit a different pattern. Because new CEOs typically enter these positions with relatively small portfolios of company stock and options, their portfolio incentives should respond quickly after risk increases. To analyze this, we estimate Eq. (2) using only observations from new CEOs' first year. This estimation will indicate whether *Exposure* is associated with different initial incentives for new CEOs. Because there are not many firms with a new CEO in the three years both before and after tail risk increases, we do not include firm-cohort fixed effects in these specifications. To control for possible baseline differences in the portfolios of newly hired CEOs in exposed and unexposed industries, we include an indicator variable for industry-cohorts that experience an increase in tail risk. The results are reported in Table 4.

After tail risk increases, newly hired CEOs are given compensation portfolios that exhibit lower exposure to firm risk. The portfolio vega is almost $50,000 lower, or about a third of a standard deviation, for a 0.01 increase in the standard deviation of stock returns for newly hired CEOs of exposed firms relative to other newly hired CEOs (column 1; $p < 0.10$). The lower portfolio vega is robust to controlling for firm size, cash compensation, and CEO tenure (column 2; $p < 0.10$).

After risk increases, new CEOs of exposed firms are also paid with lower vegas than are the CEOs they replaced. To examine within-firm changes, we compare the portfolio vega of the new CEO with that of the prior CEO. Columns 3 and 4 of Table 4 present results for the difference in portfolio vega between the new CEO and the prior CEO. After controlling for changes in firm size, cash compensation, and CEO tenure, the portfolio vega of a newly hired CEO of an exposed firm is about $85,000, or almost two-thirds of a standard deviation, lower than that of the previous CEO, relative to the change at unexposed firms (column 4; $p < 0.10$).

5. How incentives from managerial compensation affect corporate risk-taking

Our finding that CEOs' portfolios respond to changes in firms' risk environment highlights a key challenge in identifying a causal effect of incentives on corporate risk-taking. A correlation between managers' portfolio convexity and firm risk could reflect the effect of the convexity on managers' risk-taking or it might reflect the effect of firms' risky investment opportunities on boards' choices regarding pay.

The unanticipated increase in tail risk provides an opening to overcome this identification challenge. To the extent that managers are motivated by financial incentives, portfolio vega and portfolio delta affect responses to the increase in risk. As shown in Section 2.2, risk-averse managers with convex payoff structures will have less to gain from reducing risk since doing so will also decrease the expected value of their convex payoffs. Using the ex ante vega as a proxy for the (unobserved) vega managers face *after risk increases but before they respond*, we are able to identify an effect of convexity on risk-taking incentives that avoids the reverse causality critique.

To analyze the relationship between incentives and risk-taking, we augment our estimation framework in Eq. (2) to allow for a differential effect of exposure based on managers' portfolio vega and portfolio delta in the year before tail risk increases. We focus on a short window of three pre-risk and three post-risk years, and exclude any firm-years after a CEO turns over to ensure the pre-determined compensation structure is a valid proxy for the ex post incentives. Specifically, we estimate the following firm-panel regression:

$$\begin{aligned} y_{ijct} = \lambda_0 + \beta_1 Exposure_{jct} + \lambda_2 Exposure_{jct} \times \phi\left(Vega_{T-1}\right) \\ + \lambda_2 Exposure_{jct} \times \phi\left(Delta_{T-1}\right) + \omega_{tc} + \gamma_{ic} + \varepsilon_{ijct}, \end{aligned} \tag{5}$$

where y_{ijct} is one of several dependent variables of interest related to corporate risk-taking, $Vega_{T-1}$ and $Delta_{T-1}$ correspond to managers' portfolio delta and portfolio vega in the year prior to tail risk increasing, and *Exposure* and the various fixed effects are defined as above. To ease the interpretation of the estimates, $Vega_{T-1}$ and $Delta_{T-1}$ are normalized by their sample standard deviations and demeaned with respect to their sample means before they are interacted with *Exposure* (i.e., $\phi(X) = (X - \mu_X) / \sigma_X$). Therefore, λ_1 represents the effect of exposure on a firm with average portfolio vega and average portfolio delta, and λ_2 (λ_3) represents the incremental effect of exposure for a standard deviation increase in vega (delta). The standard errors are again adjusted for clustering at the industry level.

We include both vega and delta in the specification to disentangle option grants' competing effects on risk-taking incentives. On one hand, options' convex payoffs can encourage risk-taking because the manager shares all of the gains with shareholders but not all of the losses (Jensen and Meckling, 1976; Myers, 1977; Smith and Stulz, 1985; Haugen and Senbet, 1981; Smith and Watts, 1992; Gaver and Gaver, 1993; Bizjak et al., 1993; Guay, 1999; Core and Guay, 1999). Vega—the sensitivity to stock volatility—provides a measure of this convexity. On the other hand, holding options also increases a manager's sensitivity to stock price movements—delta—and to the firm's tail risk, which can discourage risk-taking (Lambert et al., 1991; Carpenter, 2000; Ross, 2004). Because the portfolio vega and portfolio delta are likely to be positively correlated, a failure to control for a manager's portfolio delta may confound the effect we are interested in—the effect of options-based convexity on risk-taking after the increase in tail risk.

The inclusion of firm-cohort fixed effects, γ_{ic}, controls for time-invariant factors, like the managers' risk tolerance, that might be correlated with the predetermined levels of vega and delta. Because we exclude observations after CEOs exit, these fixed effects also effectively control for manager fixed effects. We do not report estimates for the main effects, $Vega_{T-1}$ or $Delta_{T-1}$, because they are, by construction, time-invariant and perfectly collinear with the firm-cohort fixed effects. The coefficient on $Exposure*Vega_{T-1}$ captures the differential response for high-vega versus low-vega exposed firms relative to the similar differential response for unexposed firms. The $Exposure*Delta_{T-1}$ coefficient has a similar interpretation.

We first examine stock variance as a summary measure of firms' risk-taking. A firm's stock variance captures both exposed firms' increase in tail risk and any corporate choices, such as lower leverage and fewer R&D expenditures, that offset this increase in risk. The estimates are reported in Table 5. On average, the increase in tail risk is associated with a 0.10 increase in variance for firms with an exposure (column 1). The increase is large in magnitude (about a third of a standard deviation) and statistically significant when we add time-varying controls for firms' market-to-book ratio, debt/assets, R&D/sales, and Ln(sales) (column 3; $p < 0.10$).

The increase in firm risk is significantly larger among firms whose manager had a high portfolio vega before the increase in left-tail risk. A one standard deviation increase in a manager's portfolio vega is associated with a 0.05 larger increase in stock variance after a chemical is added to the *RoC*. Given that there is no reason to expect the increase in liability and regulatory risk from workplace exposures to be larger for firms with a higher ex ante vega, this finding suggests that managers with more convex payoffs are less likely to take actions to offset the unanticipated increase in left tail risk.

The larger increase in firm risk among managers with a high portfolio vega appears to result from a smaller reduction to financial and investment risk following the increase in tail risk. In analysis reported in Table 6, we examine firms' leverage and cash management policies as a function of their managers' incentives. The increase in tail risk is associated with a reduction in leverage for the average firm (column 1), but the decline is only statistically significant for firms with a low vega manager;[23] a one standard deviation increase in a manager's portfolio vega is associated with about a 1 percentage point smaller reduction in leverage (column 2; $p < 0.10$).

Firms' cash holdings also exhibit a differential response based on the convexity of managers' incentives. For the average firm, the increase in tail risk is associated with an increase in the ratio of cash to assets (column 4; not statistically significant), and a lower portfolio vega is associated with a larger increase in cash holdings (column 5; $p < 0.01$). This differential buildup in cash is robust to including controls for firm size, leverage, R&D, and market-to-book ratio (column 6), but the differential response in leverage is no longer statistically significant with controls for EBITDA/assets, R&D/sales, Ln(sales), and property, plant, and equipment/assets (column 3).[24,25] The association between portfolio delta and risk-taking after the increase in tail risk is the opposite. A higher delta is associated with a larger

[23] Gormley and Matsa (2011) find that the decline in leverage is statistically significant for the average Compustat firm. The estimate here is not statistically significant because our sample size is considerably smaller; our analysis also requires data on the CEOs' compensation portfolios.
[24] Again, our choice of controls in all specifications follows Hayes et al. (2012).
[25] In robustness tests reported below, we further allow the effect of *Exposure* to vary across firms in other dimensions and find that the differential response of leverage to $Vega_{T-1}$ is robust to including these controls in that specification (see Table 8).

reduction in leverage (columns 2–3) and larger increase in cash holdings (columns 5–6).[26]

Firms' investment policies also appear to be affected by the CEO's portfolio incentives. In analysis reported in Table 7, we examine firms' research and development expenditures and acquisition behavior. The results further highlight the importance of convexity. We find that the increase in tail risk is only weakly associated with a reduction in the ratio of R&D expenses to assets for the average firm, but a lower portfolio vega is strongly associated with a larger reduction in R&D expenses (column 2; $p < 0.01$). We also find that the portfolio vega is negatively associated with making diversifying acquisitions after risk increases. Gormley and Matsa (2011) find diversifying acquisitions to be a primary way firms reduce risk after such an event. Managers with a one standard deviation higher portfolio vega are 2.5 percentage points less likely to make a diversifying acquisition each year after tail risk increases. Both of the differential responses in R&D and diversifying acquisitions are robust to including additional time-varying controls (columns 3 and 6; $p < 0.01$) and are consistent with options' convex payoffs making CEOs less aggressive in cutting back on risky investments (such as R&D) and in increasing risk-reducing investments (such as diversifying acquisitions) following the jump in tail risk.

One possible concern with these results is that an omitted variable could be related to both a manager's ex ante incentive structure in the year before risk increases and the firm's response afterward. Our analysis of managers' compensation structures prior to the jump in tail risk relies on the assumption that the differences in compensation contracts, among firms which are otherwise comparable (as shown in Table 1), are not driven by factors that also affect firms' responses to the increase in risk. Contracts will differ between comparable firms because these contracts are chosen to satisfy many objectives in addition to setting incentives for risk-taking. For example, some firms may choose to grant more options for accounting reasons (Hayes et al., 2012). These other objectives provide ex ante variation in incentives that we exploit. But if factors correlated with these objectives also affect firms' response to a jump in risk, then our analysis might suffer from an omitted variable bias.

[26] The findings for portfolio delta are consistent with Gormley and Matsa (2011), who find that larger inside ownership, as measured by the fraction of shares owned by top managers, is associated with greater risk-reducing activities following the increase in tail risk.

We evaluate a wide range of potential omitted variables, including corporate financial vulnerability, external governance, and CEO age and tenure. Gormley and Matsa (2011) find that firms with greater ex ante bankruptcy risk (as measured by Altman's *z*-score), smaller size, more leverage, lower cash flows, and no dividends are more likely to engage in diversifying growth after tail risk increases, presumably because these firms experience larger increases in the likelihood of distress. Gormley and Matsa also find differences related to firms' external governance, including the proportion of institutional ownership. If these factors are related to the initial choice of compensation structure, then they—rather than incentives from the compensation—might possibly explain our findings. For example, older and more seasoned executives may be better equipped to cope with a major shock to the firm's cash flows; perhaps it is simply these CEOs for which we see no meaningful risk-reducing activities?

To examine the sensitivity of our results to these possible omitted variables, we repeat our analysis of Eq. (5) for stock variance, cash, leverage, R&D, and diversifying acquisitions but now include additional interactions between *Exposure* and the aforementioned list of potential omitted variables. Specifically, we include interactions between *Exposure* and Ln(Assets), debt/assets, modified Altman's *z*-score, cash flows/assets, institutional ownership, CEO tenure, CEO age, and an indicator for paying dividends; similar to the portfolio vega and delta, each of the interacted variables is measured as of the year prior to the increase in tail risk. We also include the additional time-varying controls traditionally included in analyses of each dependent variable. The estimates are reported in Table 8.

There is no evidence that these potential omitted variables explain the observed correlation between portfolio vega and risk-taking activities following the jump in tail risk. A higher portfolio vega is still associated with larger increases in overall firm risk, as measured by stock variance (column 1; $p < 0.10$), a smaller increase in cash holdings (column 2; $p < 0.01$) and diversifying acquisitions (column 5; $p < 0.01$), and a smaller reduction in R&D (column 4; $p < 0.01$). Moreover, although the differential effect of portfolio vega on leverage was not robust to the addition of time-varying controls in Table 6, we find that it is again statistically significant after also controlling for the possible omitted variables (column 3; $p < 0.10$).

A final possibility, which we cannot completely control for directly, is that unobservable differences in managerial risk preferences explain the differential effect of vega on risk-taking. For example, it is possible that risk-tolerant managers match with riskier firms that also happen to provide more convex incentives schemes (Graham, Harvey, Puri, forthcoming). If true, then it is possible that the underlying risk-tolerance of the CEO, rather than convexity of his/her incentives, explains the importance of portfolio vega for the observed responses.

Although we cannot rule out this possibility definitively, there are indications that it is unlikely to explain our findings. The robustness tests in Table 8 already allow for a differential effect of *Exposure* based on various measures of firm risk, including leverage, Altman's *z*-score, and dividends. If the interaction between vega and *Exposure* is being driven by some matching of risk-tolerant managers to riskier firms, then we would expect these additional interactions to dampen the effect of vega; they do not. Moreover, theory suggests that the optimal contract for managers with greater risk aversion is actually more convex so as to provide incentives for the agent to take on appropriate risk on behalf of the more risk-tolerant shareholders (see, e.g., Guay, 1999). If true and if unobservable risk preferences were driving our observed responses, we would expect to find vega associated with more risk-reducing activities after tail risk increases. Instead, we observe the opposite.

6. Conclusions and implications

Every firm is exposed to business risks, including the possibilities of large, adverse shocks. Potential sources for such shocks abound—examples include disruptive product innovations, the relaxation of international trade barriers, and changes in government regulations. We study how boards adjust CEOs' exposure to their firms' risk following a jump in left-tail risk and how incentives given by the CEOs' pre-existing portfolios of stocks and options affect their response to the change in risk. Specifically, we study what happens when a firm learns that it is exposing workers to carcinogens, which increase the risks of significant corporate legal liability and costly workplace regulations.

The results presented in this paper suggest that corporate boards respond quickly to changes in their firms' business risk by adjusting the structure of CEOs' compensation, but that the changes only slowly impact the overall portfolio incentives CEOs face. After the unexpected increase in left tail risk, corporate boards reduce CEOs exposure to their firms' risk; the sensitivity of the flow of managers' annual compensation to stock price movements and return volatility decrease. Various factors likely contribute to the board's decision, including CEOs' reduced willingness to accept a large exposure to their firms' risk and the decline in investment opportunities after risk increases. Indeed, managers act to further reduce their exposure to the firm's risk by exercising more options than do managers of unexposed firms. These changes, however, only slowly move CEOs' overall exposure to their firm's risk because the magnitude of their pre-existing portfolios continues to influence their financial exposure to the firm.

The unanticipated increase in business risk also provides an opportunity to analyze options' causal effect on corporate risk-taking. We use CEOs' pre-existing portfolio of options and stocks as a proxy for managers' portfolio immediately after the carcinogens' discovery; these incentives are pre-determined with respect to the new risk environment and not subject to the reverse causality concerns that plague existing studies of incentives and risk. We find that CEOs with more convex incentives tend not to offset the unexpected increase in risk through diversifying acquisitions, reducing leverage, cutting R&D expenditures, or by building up greater cash holdings. As a result, stock variance increases the most for high vega firms after the jump in tail risk. The findings are robust to numerous robustness checks and do not appear to be driven by omitted factors that might affect both the choice of compensation and firms' responses to the increased risk.

Overall, our results show that options affect corporate risk-taking and highlight the importance of a board structuring its executives' compensation packages to induce the desired level of risk taking. In addition, our results imply the novel insight that boards should design the convexity of managers' compensation with an eye on *potential* changes to the company's risk environment and how their executives will respond given their compensation. As our findings illustrate, more convex payoffs can dampen managerial incentives to offset unanticipated increases in business risk. Boards interested in encouraging more *aggressive* responses to future increases in business risk should use less convex incentives, whereas other boards should use more convex incentives if responding to increases in business risk is costly and undesirable to shareholders.

Appendix A. Variable definitions

<Insert Appendix Table A1 here.>

Appendix B. A mean-preserving increase in risk

In the theoretical framework described in Section 2.2, similar changes in the pre-existing portfolio's vega and the manager's differential sensitivities to deviations in risk result if we model the increase in risk as a mean-preserving increase in stock price volatility rather than as an increase in left-tail risk. The portfolio vega after a mean-preserving increase in risk is plotted in Fig. B1 for both portfolios, and the manager's marginal utility with respect to stock return volatility in a window around the optimal level of volatility is plotted in Fig. B2. The decline in the options portfolio's vega is smaller in the mean-preserving case than in the case of left-tail risk, but the decline is still greater than for the stock portfolio, which does not change (Fig. B1). Nevertheless, similar to left-tail risk, an unexpected mean-preserving increase in stock price volatility has a smaller impact on a manager's expected utility when the manager holds options rather than stocks (Fig. B2).

The similarity is intuitive. A mean-preserving increase in volatility shifts stock volatility to the right along the expected utility curve (plotted in Figure 1), whereas the increase in left-tail risk, by reducing the expected return, also shifts the manager's expected utility curve to the left. In this regard, the expected marginal utilities after each increase in risk reflect similar mappings of the utility curve's slope around the manager's optimal volatility. The difference in marginal utilities also suggests that, when a firm sets a new compensation contract, the aggressiveness with which the manager will implement the implied level of risk-taking depends on the structure of the compensation contract.

Appendix C. Decomposing changes in portfolio vega

In Section 4, we report estimates that decompose the changes in exposed CEOs' portfolio vega into three sources: changes in the vega of the pre-existing portfolio, additional vega from new option grants, and reduced vega from managers' exercising options. Only the Execucomp sample provides sufficient information on both existing and newly granted options to compute these estimates. The estimates are based on the following methodology, which is an extension of Core and Guay (2002).

To calculate the vega of CEOs' pre-existing portfolio of options in the years after left-tail risk increases ($vega^{pre}$), we apply the Core-Guay method to calculate the vega of CEOs' existing options as of year *T–1* in subsequent years by holding constant the number of options and their exercise prices but adjusting for changes in their maturity, the risk-free rate, and the firm's dividend yield, stock price, and stock volatility. To calculate the vega of CEOs' option grants after the increase in risk ($vega^{flow}$), we construct the portfolio that consists of options granted after the increase in tail risk and apply the Core-Guay method to calculate the vega of this portfolio. Lastly, to calculate the vega of options exercised ($vega^{exercised}$), we construct the portfolio of exercised options and again apply the Core-Guay method to calculate the vega of this portfolio. Because Execucomp only provides the number and value of exercised options but not their maturity or exercise price, we approximate these inputs by assuming that exercised options have the same average exercise price and maturity as the CEOs' exercisable options in the previous year.

Using the three above calculations, we can reconstruct the CEOs' overall vega in the years after the increase in tail-risk. Specifically, the "implied" portfolio vega equals $vega^{pre} + vega^{flow} - vega^{exercised}$. Despite the approximations required for these calculations, the implied vegas closely track observed vegas; on average, the implied vega is only about 5% different than the observed vega for exposed CEOs in our sample.

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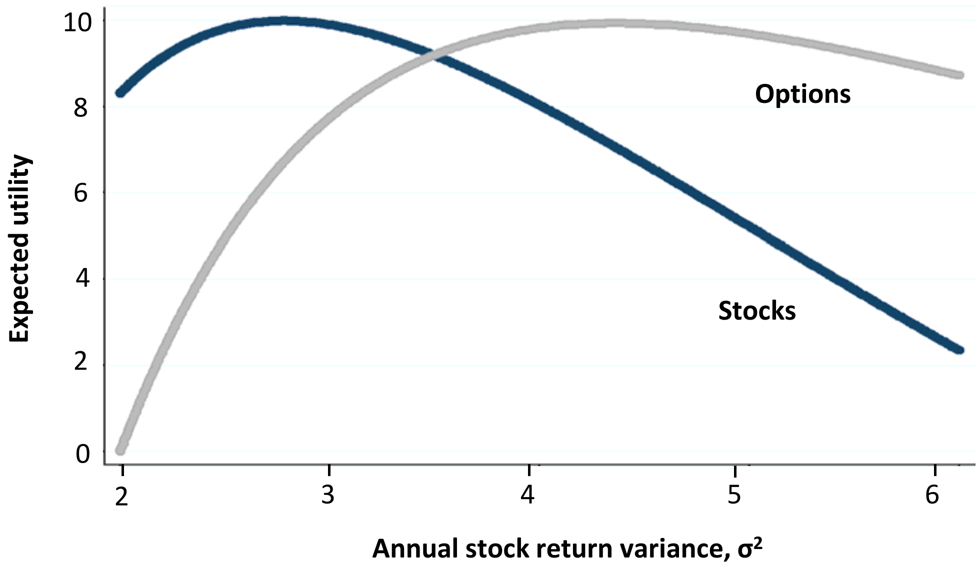

Fig. 1. Expected utility as a function of stock variance. This figure plots the expected utility of a manager as a function of the portfolio held by the manager and variance of the firm's annual stock returns. The firm's stock price is assumed to follow a lognormal return process with an initial price of $50, and the manager is assumed to have a power utility function with a coefficient of relative risk aversion of two. The options portfolio contains 10,000 options with an exercise price of $50. The options are assumed to expire in seven years. The stock portfolio contains 8,255 shares of stock. In both cases, the manager has $10 million in outside wealth. A positive affine transformation is used to rescale the level of expected utility.

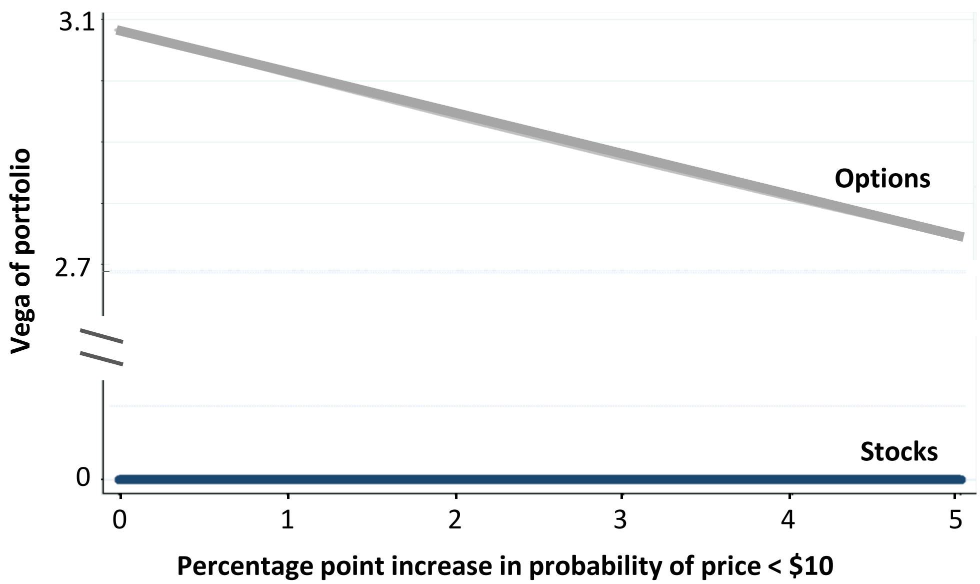

Fig. 2. Vega of portfolio after increase in left tail risk. This figure plots the portfolio vega of each manager after an increase in the probability of a left-tail risk. The portfolio vega is calculated assuming a zero dividend yield, a risk free rate of five percent, and that the firm was at the manager's optimal level of stock volatility (shown in Figure 1) prior to the increase in left-tail risk. The left tail risk is modeled as an increase in the probability of a stock price realization below $10.

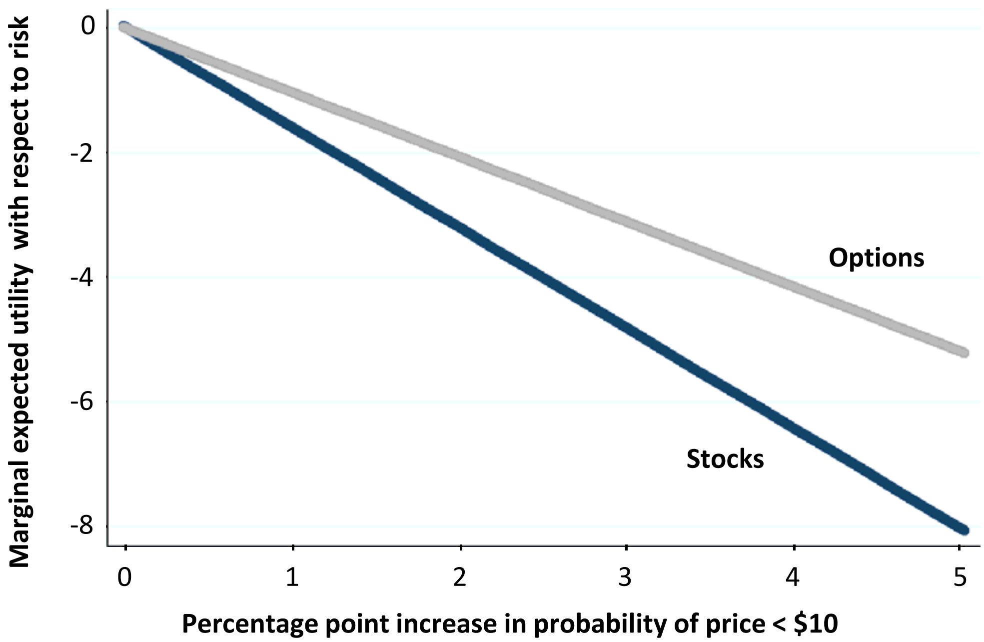

Fig. 3. Marginal expected utility with respect to risk after increase in left tail risk. This figure plots the manager's marginal utility of risk after an increase in the probability of a left-tail risk. This is the numerical derivative of the manager's expected utility (shown in Figure 1) with respect to volatility, evaluated at the manager's previously optimal level of stock volatility. The left tail risk is modeled as an increase in the probability of a stock price realization below $10.

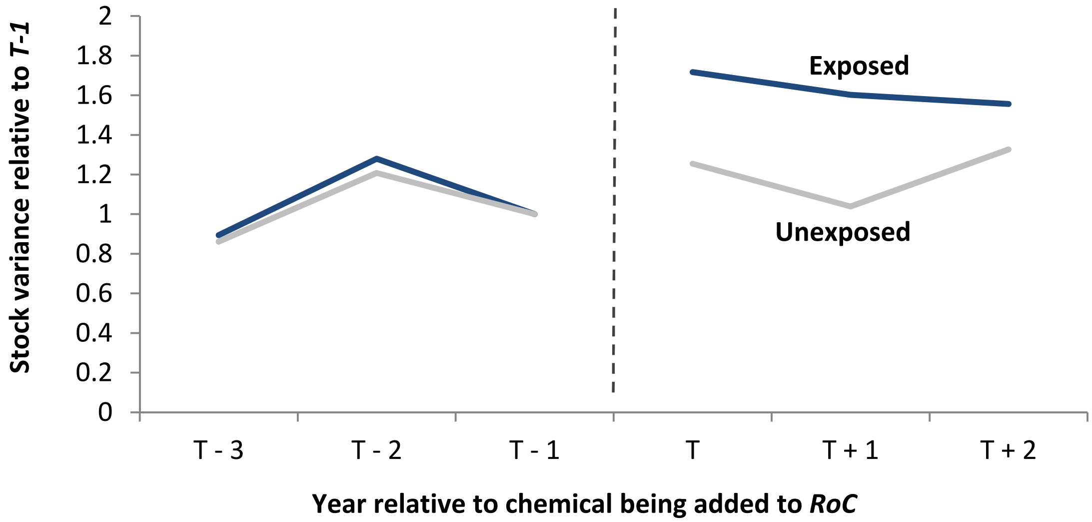

Fig. 4. Stock variance of exposed and unexposed firms. This figure plots the relative average annualized daily stock variance for exposed and unexposed firms using the same sample and definitions of exposed and unexposed firms from Table 1. The average annualized stock variance is indexed to one in the year prior to a chemical being added to the *Report on Carcinogens*.

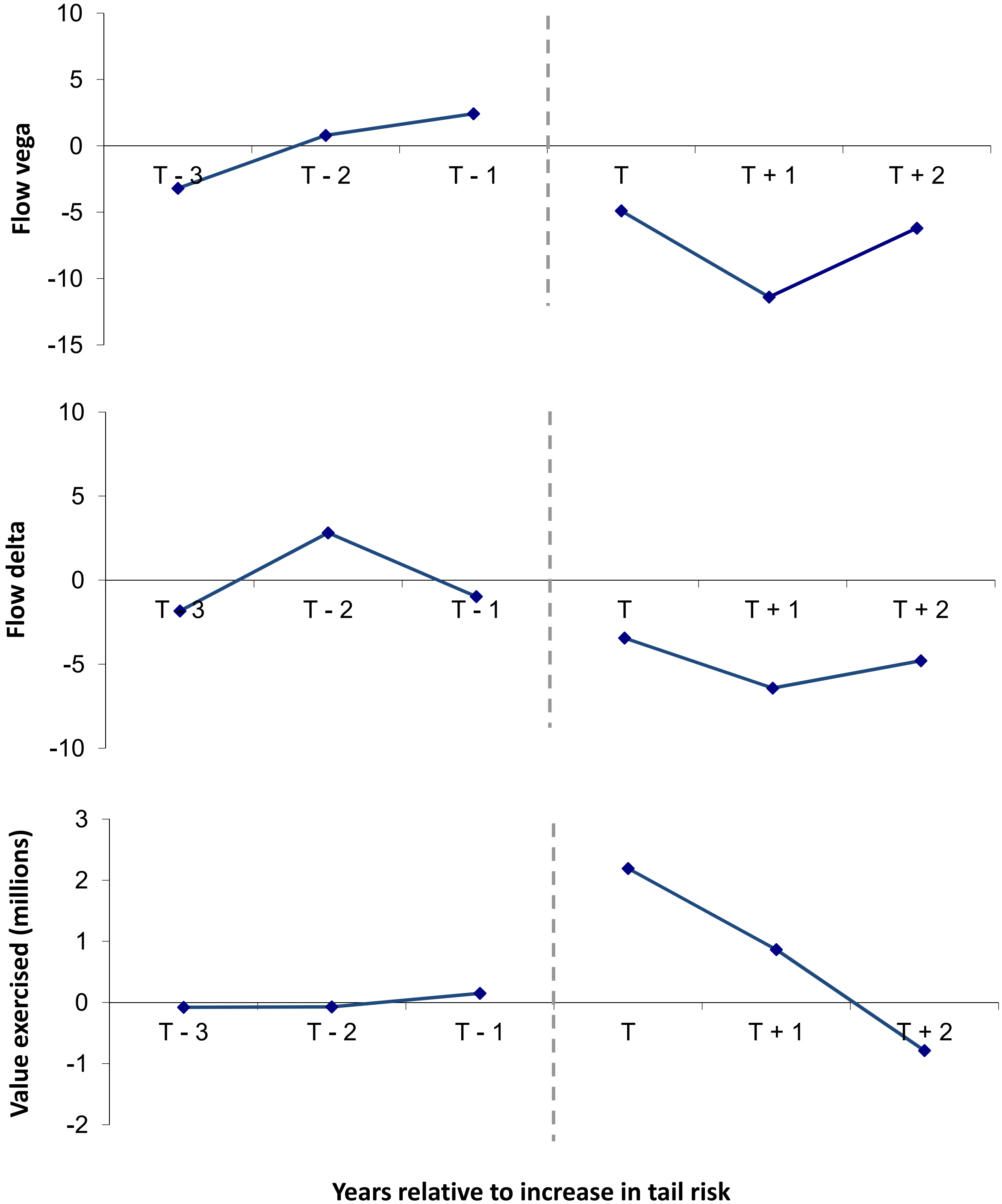

Fig. 5. Effect of exposure on flow vega, flow delta, and value exercised by year. This figure reports the point estimates from firm-panel regressions of flow vega, flow delta, and value of options exercised onto an indicator for exposure, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The specifications are the same as those reported in Table 2, columns 1, 4, and 7, except that the effect of exposure is allowed to vary by year.

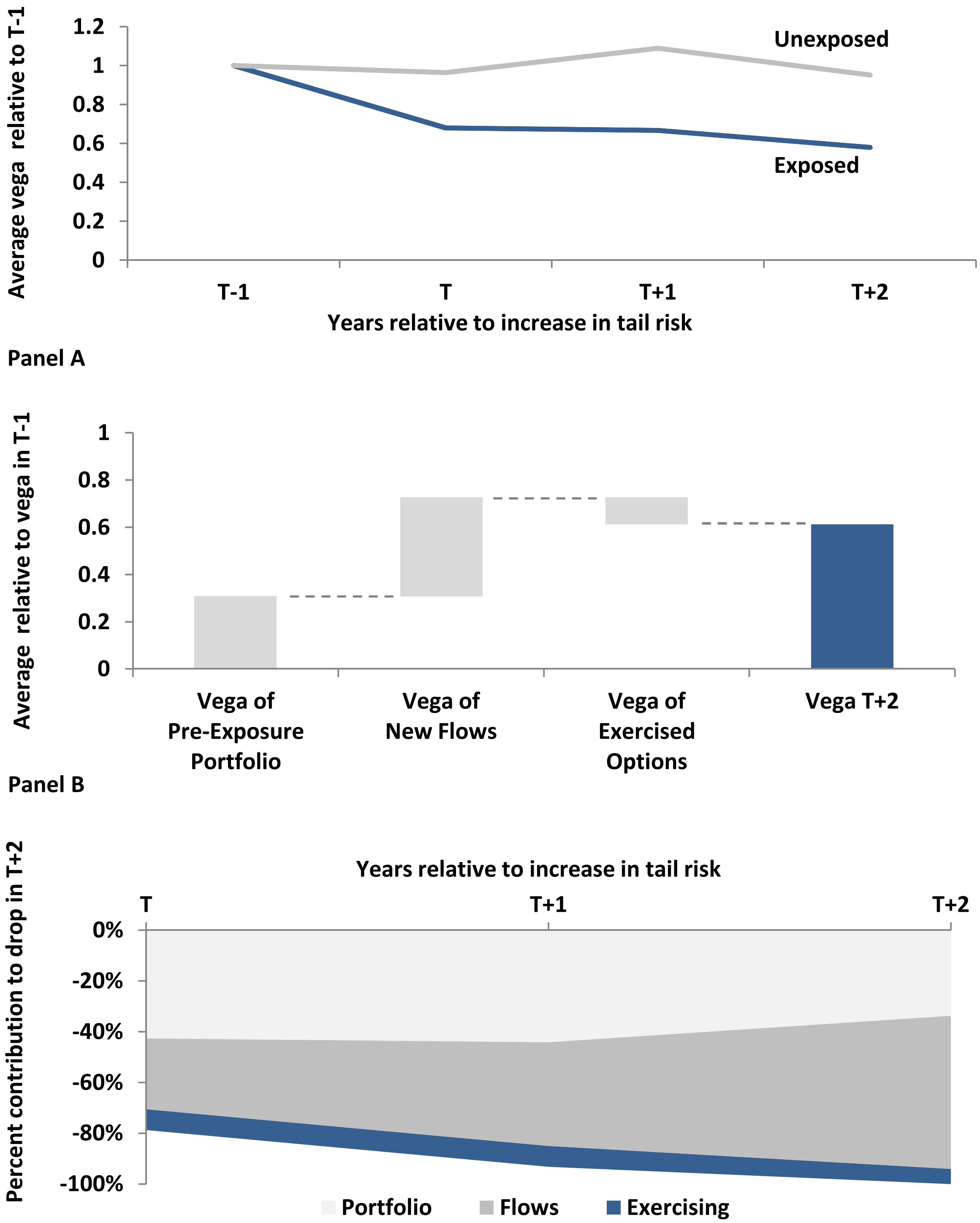

Fig. 6. Deconstructing the vega for exposed firms in year *T+2*. Panel A of this figure reports the average vega of exposed and unexposed firms in the Execucomp sample by year relative to the increase in tail risk. Panel B then desconstructs the overall, average vega of exposed managers in year *T+2* into its three components: vega from managers' pre-exposure portfolio, new flows, and the drop in vega from exercising of options. Panel C then plots the percent contribution of each source to the total drop in year *T-2* relative to a counterfactual where exposed firms continue exercising the same number of options as in year *T-1* and exhibit the same growth rate in their portfolio vega and flow vega as unexposed firms during the same time period.

Table 1
Ex-ante firm characteristics.

This table reports summary statistics for firm characteristics in the three years before a new chemical was added to the *Report on Carcinogens*. The mean and standard deviation (in parentheses) for each variable are reported separately for two samples of firms. Column 1 reports estimates for firms in 4-digit SIC industries for which more than 5% of employees were observed to be exposed to the chemical in the 1981–1983 National Occupational Exposure Survey. Column 2 reports estimates for other firms in the same Fama-French 48-industry classification. Column 3 reports the *p*-value from a *t*-test of the difference between exposed and unexposed firms, where the standard errors are adjusted for clustering at the 4-digit SIC industry level. The sample is restricted to firms with non-missing observations for portfolio vega and delta in the year prior to the new chemical being added to the *Report on Carcinogens*.

	Exposed	**Unexposed**	***p*-value of difference**
	(1)	(2)	(3)
Firm characteristics			
Stock variance	0.243	0.177	0.350
	(0.211)	(0.189)	
Ln(assets)	7.151	7.438	0.472
	(1.522)	(1.396)	
Market-to-book ratio	0.026	0.026	0.992
	(0.165)	(0.063)	
Cash flows / assets	0.155	0.147	0.419
	(0.088)	(0.092)	
Compensation characteristics			
Portfolio delta	326.2	519.3	0.299
	(716.0)	(2,537)	
Portfolio vega	41.74	27.60	0.591
	(139.5)	(112.2)	
Ln(total pay)	6.972	6.920	0.761
	(0.955)	(1.011)	
Options / total pay	0.313	0.265	0.562
	(0.311)	(0.254)	
Observations	143	341	
# of industries	43	82	

Table 2
Flow delta and vega, options exercised, and the effect of exposure.

This table reports coefficients from firm-panel regressions of flow vega, flow delta, and value of options exercised on an indicator for exposure, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The exposure indicator equals one if more than 5% of employees in the firm's 4-digit SIC industry were observed to be exposed to a chemical listed in the most recent edition of the *Report on Carcinogens* (*RoC*), as reported in the 1981–1983 National Occupational Exposure Survey. The sample includes firm-year observations in the three years before and three years after each new chemical listing in the *RoC* for firms with non-missing portfolio vega and delta in the year prior to the new *RoC* listing. Columns 3, 6, and 9 exclude observations after a new chemical listing for which the CEO is different than the CEO in the year prior to the chemical being listed. Columns 2–3, 5–6, and 8–9 include firms' Ln(assets) and CEOs' tenure and salary + bonus as additional controls. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. ***significant at the 1% level; **significant at the 5% level; *significant at 10% level.

Dep. variable =	**Flow vega** *Mean = 17.52* *St. Dev. = 55.90*			**Flow delta** *Mean = 20.37* *St. Dev. = 83.06*			**Value of options exercised** *Mean = 912.9* *St. Dev. = 4,546*		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Exposure	-7.60**	-10.00***	-8.90**	-12.88***	-24.61*	-25.21*	790.8	1,063***	1,184***
	(3.11)	(3.76)	(3.89)	(4.70)	(13.67)	(14.40)	(575.9)	(397.9)	(429.2)
Observations	2,378	1,367	1,211	2,363	1,367	1,211	2,505	1,439	1,277
R^2	0.02	0.05	0.05	0.01	0.04	0.05	0.02	0.09	0.10
# of firms	469	309	264	469	309	264	484	320	275
Additional controls		X	X		X	X		X	X
Excludes new CEOs after *T* – 1			X			X			X
Fixed effects:									
Firm-cohort	X	X	X	X	X	X	X	X	X
Year-cohort	X	X	X	X	X	X	X	X	X

Table 3
Long-term effect of exposure on portfolio delta and vega.

This table reports coefficients from CEO-level regressions of post-exposure changes in portfolio vega and delta on an indicator for exposure and cohort fixed effects. The exposure indicator is defined as in Table 2. The sample includes CEOs with non-missing portfolio vega and portfolio delta in the year prior to the *RoC* listing and excludes CEOs that are no longer present in the year in which the post-exposure change in incentives is calculated. The dependent variables are the three-, four-, five-, and six-year changes in portfolio vega and delta (columns 1–2, 3–4, 5–6, and 7–8, respectively) relative to the year prior to a chemical being added to the *RoC*. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. **significant at the 5% level; *significant at 10% level.

	3-year Δ in incentives *[T+2] versus [T-1]*		**4-year Δ in incentives** *[T+3] versus [T-1]*		**5-year Δ in incentives** *[T+4] versus [T-1]*		**6-year Δ in incentives** *[T+5] versus [T-1]*	
Dep. variable =	**Portfolio vega**	**Portfolio delta**	**Portfolio vega**	**Portfolio delta**	**Portfolio vega**	**Portfolio delta**	**Portfolio vega**	**Portfolio delta**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Exposure	-24.60	-181.7	-43.71	-346.4**	-43.66	-448.2*	-55.31*	-483.8**
	(26.06)	(132.0)	(27.49)	(151.8)	(28.35)	(229.2)	(28.95)	(225.1)
Observations	334	334	262	262	251	251	218	218
R^2	0.02	0.05	0.02	0.05	0.05	0.02	0.06	0.02
Excludes new CEOs after *T* – 1	X	X	X	X	X	X	X	X
Cohort fixed effects	X	X	X	X	X	X	X	X

Table 4
Portfolio vega of newly hired CEOs and the effect of exposure.

This table reports coefficients from CEO-level regressions of the level and change of portfolio vega on an indicator for exposure, year-cohort fixed effects, and a cohort-level indicator for operating in an industry with an exposure. The exposure indicator is defined the same as in Table 2. The sample includes observations from a CEO's first year in office for CEOs hired in the three years before and three years after each new chemical listing in the *RoC*. To ensure the same sample of firms as in earlier specifications, we continue to restrict the sample to firms with non-missing portfolio vega and portfolio delta in the year prior to the new *RoC* listing. The dependent variable in columns 1–2 is the initial portfolio vega of the newly hired CEO, and the dependent variable in columns 3–4 is the difference between the initial portfolio vega of the new CEO and the portfolio vega of the outgoing CEO. Column 2 includes firms' Ln(assets) and the new CEOs' tenure and salary + bonus as additional controls, and column 4 includes the changes in these variables as controls. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. *significant at 10% level.

Dep. variable =	**Portfolio vega**		**Δ portfolio vega from prior CEO**	
	(1)	(2)	(3)	(4)
Exposure	-49.4*	-30.3*	-111.5	-84.6*
	(25.8)	(17.7)	(67.2)	(42.3)
Observations	175	149	167	71
R^2	0.09	0.45	0.08	0.36
Exposed industry-cohort indicator	X	X	X	X
Year-cohort fixed effects	X	X	X	X
Additional controls		X		X

Table 5

Stock variance and the effect of exposure and incentives.

This table reports coefficients from firm-panel regressions of annualized daily stock variance on an indicator for exposure and its interactions with portfolio vega and portfolio delta in the year prior to an increase in tail risk, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The exposure indicator is defined the same as in Table 2. The sample includes firms with non-missing portfolio vega and portfolio delta in the year prior to the *RoC* listing and excludes firm-year observations after a new chemical listing for which the CEO is different than the CEO in the year prior to the chemical being listed. For ease of interpreting the exposure coefficient and its interactions, the portfolio vega and portfolio delta are demeaned and rescaled by their sample standard deviation [i.e., $\phi(X) = (X - \mu_X)/\sigma_X$] before being interacted with *Exposure*. Column 3 includes firms' market-to-book ratio, debt/assets, R&D/sales (with missing values replaced with zeros), and Ln(sales) as additional controls. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. **significant at the 5% level; *significant at 10% level.

Dep. variable =	**Stock variance** *Mean = 0.23* *St. Dev. = 0.29*		
	(1)	(2)	(3)
Exposure	0.102	0.094	0.097*
	(0.068)	(0.059)	(0.056)
Exposure × ϕ(Vega $_{T-1}$)		0.049**	0.047**
		(0.019)	(0.019)
Exposure × ϕ(Delta $_{T-1}$)		0.023	0.039
		(0.053)	(0.050)
Observations	2,620	2,620	2,562
R^2	0.22	0.23	0.24
# of firms	484	484	480
Excludes new CEOs after *T* – 1	X	X	X
Additional controls			X
Fixed effects:			
Firm-cohort	X	X	X
Year-cohort	X	X	X

Table 6

Financial risk and the effect of exposure and incentives.

This table reports coefficients from firm-panel regressions of debt/assets and cash/assets on an indicator for exposure and its interactions with portfolio vega and portfolio delta in the year prior to an increase in tail risk, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The specification and sample are the same as reported in Table 5. For ease of interpreting the exposure coefficient and its interactions, the portfolio vega and portfolio delta are demeaned and rescaled by their sample standard deviation [i.e., $\phi(X) = (X - \mu_X)/\sigma_X$] before being interacted with *Exposure*. The additional controls follow Hayes et al. (2012); in column 3, they include firms' EBITDA/assets, R&D/sales (with missing values replaced with zeros), Ln(sales), and property, plant, and equipment/assets; and in column 6, they include firms' market-to-book ratio, debt/assets, R&D/sales (with missing values replaced with zeros), and Ln(sales). Standard errors, adjusted for clustering at the industry level, are reported in parentheses. ***significant at the 1% level; **significant at the 5% level; *significant at 10% level.

Dep. variable =	**Debt/assets** *Mean = 0.25* *St. Dev. = 0.17*			**Cash/assets** *Mean = 0.067* *St. Dev. = 0.094*		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	-0.005	-0.006	-0.014	0.003	0.004	0.005
	(0.012)	(0.013)	(0.011)	(0.007)	(0.007)	(0.007)
Exposure × ϕ(Vega $_{T-1}$)		0.009*	0.005		-0.006***	-0.006***
		(0.005)	(0.004)		(0.002)	(0.002)
Exposure × ϕ(Delta $_{T-1}$)		-0.056**	-0.066***		0.021***	0.019**
		(0.023)	(0.018)		(0.006)	(0.008)
Observations	2,597	2,597	2,588	2,230	2,230	2,210
R^2	0.03	0.04	0.11	0.04	0.04	0.07
# of firms	481	481	481	454	454	452
Excludes new CEOs after *T* – 1	X	X	X	X	X	X
Additional controls			X			X
Fixed effects:						
Firm-cohort	X	X	X	X	X	X
Year-cohort	X	X	X	X	X	X

Table 7
Investment risk and the effect of exposure and incentives.

This table reports coefficients from firm-panel regressions of R&D/assets and an indicator for undertaking a diversifying acquisition on an indicator for exposure and its interactions with portfolio vega and portfolio delta in the year prior to an increase in tail risk, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The specification and sample are the same as reported in Table 5. For ease of interpreting the exposure coefficient and its interactions, the portfolio vega and portfolio delta are demeaned and rescaled by their sample standard deviation [i.e., $\phi(X) = (X - \mu_X)/\sigma_X$] before being interacted with *Exposure*. The additional controls follow Hayes et al. (2012); in column 3, they include CEOs' salary + bonus and firms' Ln(sales), market-to-book ratio, sales growth, debt/assets, stock return, and surplus cash/assets; and in column 6, they include CEOs' tenure and salary + bonus and firms' Ln(sales), market-to-book ratio, EBITDA/assets, debt/assets, stock return, and a CEO exit indicator. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. ***significant at the 1% level; **significant at the 5% level.

Dep. variable =	**R&D/assets** *Mean = 0.049* *St. Dev. = 0.048*			**Diversifying acq. indicator** *Mean = 0.13* *St. Dev. = 0.34*		
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	-0.003	-0.004	-0.001	0.024	0.029	0.030
	(0.002)	(0.002)	(0.002)	(0.034)	(0.036)	(0.037)
Exposure × ϕ(Vega $_{T-1}$)		0.002***	0.004***		-0.025***	-0.022***
		(0.0002)	(0.0003)		(0.006)	(0.008)
Exposure × ϕ(Delta $_{T-1}$)		-0.002	0.005		0.055**	0.034
		(0.002)	(0.005)		(0.026)	(0.035)
Observations	1,361	1,361	809	2,645	2,645	2,576
R^2	0.06	0.06	0.22	0.02	0.02	0.02
# of firms	259	259	204	484	484	480
Excludes new CEOs after *T* – 1	X	X	X	X	X	X
Additional controls			X			X
Fixed effects:						
Firm-cohort	X	X	X	X	X	X
Year-cohort	X	X	X	X	X	X

Table 8
Controlling for possible omitted variables.

This table reports coefficients from firm-panel regressions of annualized daily stock variance, cash/assets, debt/assets, R&D/assets, and an indicator for undertaking a diversifying acquisition on an indicator for *Exposure* and its interactions with portfolio vega and portfolio delta in the year prior to an increase in tail risk, firm-by-cohort fixed effects, and year-by-cohort fixed effects. The specifications, sample, and controls are the same as those reported in columns 3 and 6 of Tables 5–7, but additional interactions between *Exposure* and various CEO and firm characteristics in the year prior to a new *RoC* listing are added as controls. The following characteristics are each interacted separately with *Exposure*: Ln(assets), a dividend indicator, debt/assets (except for column 3), modified Altman *z*-score, cash flows/assets, institutional ownership, CEO tenure, and CEO age. Standard errors, adjusted for clustering at the industry level, are reported in parentheses. ***significant at the 1% level; **significant at the 5% level; *significant at the 10% level.

Dep. variable =	**Stock variance**	**Cash/ assets**	**Debt/ assets**	**R&D/ assets**	**Diversifying acquisition**
	(1)	(2)	(3)	(4)	(5)
Exposure	0.147***	0.0221**	-0.003	0.005	0.057
	(0.040)	(0.011)	(0.019)	(0.003)	(0.052)
Exposure × ϕ(Vega $_{T-1}$)	0.026*	-0.006***	0.007*	0.002***	-0.033***
	(0.015)	(0.002)	(0.004)	(0.000)	(0.008)
Exposure × ϕ(Delta $_{T-1}$)	0.039	0.0213**	-0.075***	0.001	0.056
	(0.043)	(0.009)	(0.021)	(0.002)	(0.044)
Observations	1,393	1,287	1,403	772	1,403
R^2	0.35	0.06	0.07	0.10	0.06
# of firms	253	246	253	144	253
Excludes new CEOs after *T* – 1	X	X	X	X	X
Additional Exposure interactions	X	X	X	X	X
Additional controls	X	X	X	X	X
Fixed effects:					
Firm-cohort	X	X	X	X	X
Year-cohort	X	X	X	X	X

Table A1
Variable Definitions

Dependent variables	
Portfolio delta	Manager's change in wealth (expressed in thousands of dollars) for a 1% increase in the firm's stock price. Calculated from managers' complete portfolio of stock and options from Execucomp or Yermack (1995) and the methodology from Core and Guay (2002). The value of the option portfolio is the sum of the Black-Scholes values of the newly granted options and previously granted unexercisable and exercisable options. Yermack (1995) contains information on a manager's previously granted stock but not options, so we use information only on options granted in the last year to calculate the delta for those options.
Portfolio vega	Manager's change in wealth (expressed in thousands of dollars) for a 0.01 increase in the annualized standard deviation of firm's stock returns. Calculated from managers' complete portfolio of stock and options from Execucomp or Yermack (1995) and the methodology from Core and Guay (2002). See definition of Portfolio Delta for more details.
Flow delta	Same as Portfolio Delta but calculated using only stocks and options granted in given year. In Execucomp the number of shares granted is approximated using rstkgrnt/prccf, and in the Yermack sample, it is approximated using othcomp/endprice.
Flow vega	Same as Portfolio Vega but calculated using only options granted in given year.
Value exercised	Calculated as opt_exer_val in Execucomp and optgains in Yermack (1995) data.
Cash/assets	Calculated from Compustat using ch/at.
Debt/assets	Calculated from Compustat using (dltt + dlc)/at.
Diversifying acquisition indicator	Calculated using SDC's Mergers and Acquisitions Database. Indicator equal to one if the firm does an acquisition where its primary SIC industry does not coincide with any SIC code of the target firm.
R&D/assets	Calculated from Compustat using xrd/at.
Stock variance	Calculated from CRSP using sum of squared daily returns over the year. For firms with less than 252 days of trading, it is adjusted to be comparable.

Firm-level controls (from Compustat)

Cash flows/assets	(oiadp - accruals) / at, where accruals = (act_t - act_{t-1}) - (che_t - che_{t-1}) - (lct_t - lct_{t-1}) + (dlc_t - dlc_{t-1}) - dp
EBITDA/assets	oibdp/at
Ln(assets)	ln(at)
Ln(sales)	ln(sale)
Market-to-book ratio	(csho * prcc_c)/ceq
PP&E/assets	ppent/at
R&D/sales	min(0, xrd/sale)
Sales growth	ln($sale_t$) - ln($sale_{t-1}$)
Stock return	($prcc\_c_t$ -$prcc\_c_{t-1}$)/$prcc\_c_{t-1}$
Surplus cash/assets	(oancf-dpc+xrd)/at

CEO-level controls

CEO age	Age of CEO obtained from Disclosure database between 1990 and 2004, thanks to James S. Linck.
CEO exit	Indicator that equals one in year that CEO exit occurs.
CEO tenure	Number of years a manager has been CEO, which is obtained from Disclosure database between 1990 and 2004, thanks to James S. Linck. Missing values are imputed when possible.
Ln(total pay)	Calculated as Ln(tdc1) in Execucomp and Ln(salbon + othcomp + grantval) in Yermack (1995) data.
Options/total pay	Calculated as option_awards_blk_value/tdc1 in Execucomp and grantval/(salbon + othcomp + grantval) in Yermack (1995) data.
Salary + bonus	Calculated as salary + bonus in Execucomp and salbon in Yermack (1995) data.

Note: All variables that represent a dollar value, including delta and vega, are adjusted for inflation using the annual average CPI index for urban consumers from the Bureau of Labor Statistics.

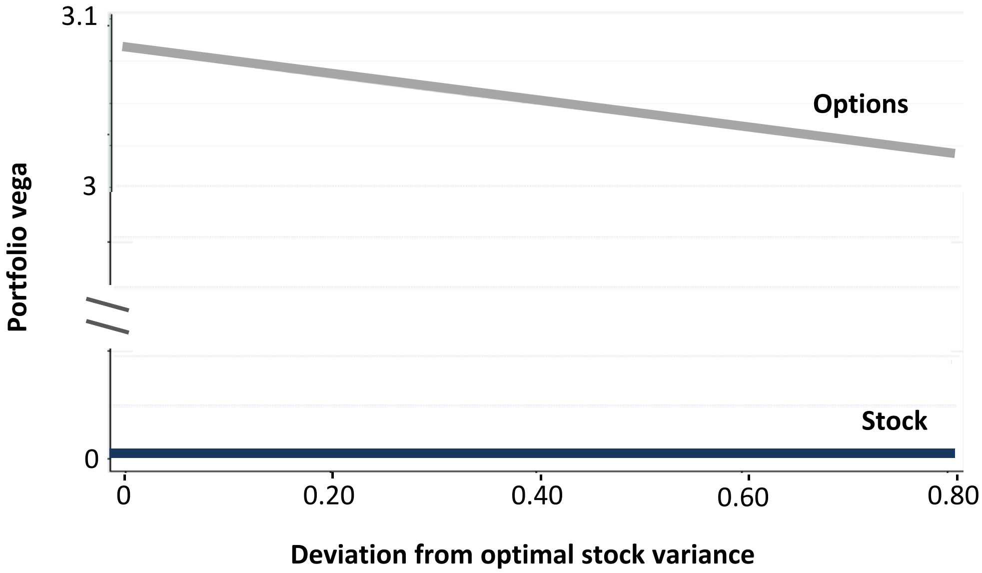

Fig. B1. Vega of portfolio after a mean-preserving increase in risk. This figure plots the portfolio vega after a mean-preserving increase in stock variance for the options-only portfolio. The portfolio vega is calculated assuming a zero dividend yield, a risk-free rate of five percent, and that the firm was at the manager's optimal level of stock volatility (shown in Figure 1) prior to the increase in risk.

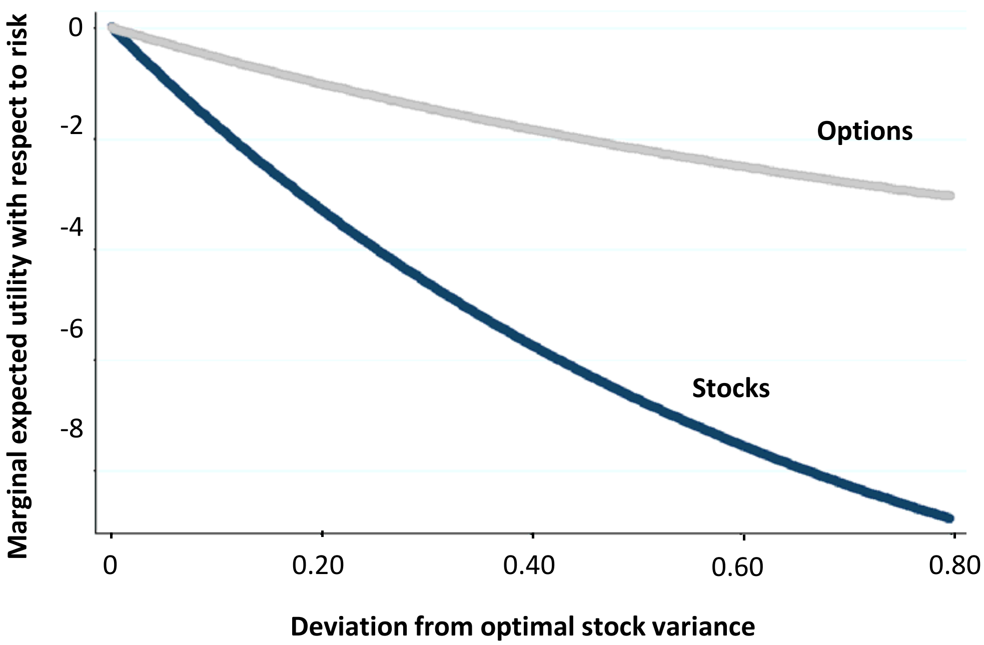

Fig. B2. Marginal expected utility with respect to risk after a mean-preserving increase in risk. This figure plots the manager's marginal utility of risk after a mean-preserving increase in stock variance. This is the numerical derivative of the manager's expected utility (shown in Figure 1) with respect to variance at points above the manager's previously optimal level of stock variance.