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Abstract

We investigate the suitability of securitization as an alternative to reinsurance for the purpose of transferring natural catastrophe risk. We characterize the conditions under which one or the other form of risk transfer dominates using a setting in which reinsurers and traders in financial markets produce costly information about catastrophes. Such information is useful to insurers: along with the information produced by insurers themselves, it reduces insurers' costly capital requirements. However, traders who seek to benefit from trading in financial markets may produce 'too much' information. This instance of the Hirshleifer effect may make risk transfer through securitization prohibitively costly.

1 Introduction

Traditional catastrophe reinsurance has in recent years come under scrutiny in the academic literature. In his study of the market for catastrophe risk, Froot (2001) shows that insurers should optimally reinsure against large catastrophic events first. Moreover, since catastrophe risks are uncorrelated with aggregate financial wealth, reinsurance premia should reflect expected losses. Both of these conjectures are invalidated by Froot's study of the aggregate profile of reinsurance purchases: insurers tend to reinsure medium-size losses, but retain (rather than reinsure) their large-event risks; the reinsurance premia they pay often are a multiple of expected losses. Froot explains these phenomena mainly by the inefficiencies that characterize the supply of capital to reinsurance companies and by these companies' excessive market power. Doherty (1997) argues that these inefficiencies of the reinsurance market should spur the development of alternate forms of risk transfer, such as securities traded on financial markets. Because financial markets can draw on a larger, more liquid and more diversified pool of capital than the equity of reinsurance companies, they should have a strong advantage over reinsurance in financing catastrophe risk (Durbin, 2001). Cummins and Weiss (2009) document the growing use of securitization in financial markets to transfer catastrophe risk. They provide evidence of market takeoff, especially as regards catastrophe bonds. As noted by Cummins and Weiss, the success of over-the-counter (OTC) traded catastrophe bonds has not extended to exchange-traded catastrophe instruments: there has been little to no interest in the futures and option contracts introduced by exchanges as diverse as the Chicago Board of Trade (CBOT), the Bermuda Commodities Exchange (BCOE), the New York Mercantile Exchange (NYMEX), the Chicago Mercantile Exchange (CME), and the Insurance Futures Exchange (IFEX); at the time of writing, only the contracts introduced in 2007 by the CME appear still to be trading, at low volumes.

In this study, we compare reinsurance and securitization in financial markets for the purpose of transferring natural catastrophe risk and characterize the conditions under which one or the other form of risk transfer dominates. We consider the case of an insurer exposed to natural catastrophe risk. The insurer seeks to supplement the costly information it has produced about possible losses with information obtained from a reinsurer or from prices in financial markets. Such information is valuable to the insurer, for it decreases that insurer's costly capital requirements: the better the insurer understands the risk to which it is exposed,

the lesser the amount of capital the insurer needs to guard against such risk. The insurer also seeks to take advantage of the reinsurer and the financial markets' lower cost of capital. Reinsurers are considered to have lower cost of capital than insurers because they are larger and more diversified. The financial markets' cost of capital is low for two reasons: i) margin requirements in financial markets differ from equity investments in reinsurance companies in not involving the agency problems that raise the cost of external capital;[1] ii) natural catastrophe risk has had low correlation with aggregate wealth (Cummins and Weiss, 2009).

We ask which form of risk transfer, reinsurance or securitization in financial markets, minimizes the total cost of bearing catastrophe risk to the insurer. Total cost includes the cost of the capital that must be held by the insurer, that of the capital that must be held by the reinsurer to which a fraction of the risk has been transferred, and the cost of producing the information that helps both insurer and reinsurer decrease capital requirements and provides informed traders in financial markets with the opportunity to profit at the expense of liquidity traders. We find that informed traders who seek to benefit from trading in financial markets may in some cases produce more information than warranted by the primary objective of decreasing insurer capital requirements; there is 'too much' information. This is an instance of the 'Hirshleifer Effect' (Hirshleifer, 1971); it is costly to insurers, who bear the cost of information production through the discount they must offer liquidity traders to compensate these traders for the losses they expect to sustain informed traders.

We use a rich setting to investigate the key factors that affect the relative cost of risk transfer through reinsurance and securitization. In our setting, there are fixed and variable costs to producing information; the larger the variable costs incurred, the higher the quality of the information. There is also some substitution between fixed and variable costs, in the sense that the aggregation of many pieces of lower quality information can result in a higher quality piece of aggregated information. Such aggregation characterizes financial markets (Grossman, 1989); the increase in information quality it makes possible is greater, the more complementary—the less redundant—the many pieces of information produced by informed traders.

We find that the production of too much information at too high a cost in financial markets is more likely i) where the fixed costs of producing information are high, ii) where

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[1]See Froot, Scharfstein, and Stein (1993), Froot and Stein (1998), and Froot (2007) for a discussion of such costs. We discuss this issue in further detail in Section 3.3.2.

the variable costs of producing information are low, iii) where there are many liquidity traders, and iv) where losses are highly uncertain. To understand the intuition for these results, recall that reinsurance and securitization in financial markets represent two alternative mechanisms for providing the insurer with information. Financial markets are at a disadvantage where it is preferable to have one party—the reinsurer—produce a single piece of high quality information to supplement that produced by the insurer than to have many parties—informed traders in financial markets—produce numerous pieces of generally lower quality information. Where variable costs are low relative to fixed costs, the indirect production of high quality information through aggregation in financial markets is less efficient than the direct production of that information by a single reinsurer that incurs both the fixed and the variable costs of producing high quality information; reinsurance dominates securitization. Such dominance is generally compounded by the presence of many liquidity traders and by large uncertainty about losses: the greater the presence of liquidity traders and loss uncertainty, the greater informed traders' profit opportunities, the greater these traders' incentive to produce information for the purpose of taking advantage of these opportunities; this exacerbates the problem of excess information production in financial markets. Result iv) is consistent with Hagendorff, Hagendorff, and Keasey's (2010) finding that stock market reaction to catastrophe bond issuance is higher for issuers with less volatile loss ratios. Result iii) is consistent with the aforementioned success of catastrophe bonds and relative failure of exchange-traded catastrophe futures and options: there are few, if any liquidity traders in OTC markets, unlike in exchanges.[2]

Redundancy in the information produced—how similar are the pieces of information produced by informed traders in the financial markets—favors reinsurance where there is large loss uncertainty and securitization in financial markets where there is little. Where large loss uncertainty elicits the need for information to supplement that produced by the insurer, there is much inefficiency producing numerous pieces of redundant information; redundancy favors reinsurance over securitization. Where, in contrast, there is little loss uncertainty and little need for supplemental information, redundancy decreases informed traders' profit opportunities, thereby deterring these traders' entry. There is little information production in financial markets, which come to dominate reinsurance by virtue of their lower cost of

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[2]Most catastrophe bonds have been sold under Rule 144A to Qualified Institutional Buyers (QIBs); few QIBs can be considered liquidity traders, in the sense of consistently sustaining trading losses to informed traders.

capital.

The paper proceeds as follows. Section 2 reviews the literature. Section 3 presents and solves our model of an insurer that seeks to transfer a fraction of the risks he has insured either through reinsurance or through securitization. Section 4 considers the two polar cases of no and full redundancy for the purpose of providing some preliminary intuition and illustrating some of the tradeoffs involved. Section 5 identifies the determinants of the preferred forms of risk transfer. Section 6 concludes.

2   Literature Review

Our paper is in the line of a number of papers that have compared private and public financing; in our case, reinsurance is private financing and securitization public. Examples of such papers are Bolton and Freixas (2000), Boot and Thakor (1997), Chemmanur and Fulghieri (1994), and Subrahmanyam and Titman (1999). In many of these papers, the basic problems are those of moral hazard and adverse selection. We acknowledge the importance of moral hazard and adverse selection in natural catastrophe risk transfer; indeed, we rely on such considerations to preclude the complete transfer of risk from insurer to reinsurer or financial markets (see Section 3). We follow Carter (1983) and Mayers and Smith (1990) in deeming information provision to be no less important.[3]   Boot and Thakor examine information provision in public markets but not in private. Subrahmanyam and Titman compare private and public financing for the purpose of information provision; we adapt and modify their model for our purpose. Our model differs from theirs in many respects: it includes variable as well as fixed costs of producing information and develops an explicit measure of information redundancy.

There is an extensive literature on the use of securitization in financial markets for transferring catastrophe risk (D'Arcy and France, 1992; Niehaus and Mann, 1992). Such literature has examined the advantages of financial markets, emphasizing their risk disaggregation (Doherty and Schlesinger, 2002) and capital supply (Jaffee and Russell, 1997) properties, and

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[3]Anecdotes are worth what they are worth, but it is noteworthy that, in his closing remarks at a joint industry/academia conference on new forms of risk transfers, the chairman of a large reinsurance company felt it necessary gently to chide presenters for not having discussed what he deemed a primary role of his firm and of reinsurers more generally, specifically helping insurers structure the insurance contracts they offer. We provide more formal evidence of information provision in Section 3.1.

their lack of exposure to moral hazard and to default risk (Doherty, 1997; Lakdawalla and Zanjani, 2006). Froot (2001) measures the transaction costs involved in catastrophe risk securitization; he finds these to be quite moderate. Harrington and Niehaus (1999) and Cummins, Lalonde, and Phillips (2004) measure the basis risk involved in using standardized catastrophe insurance contracts; they find such contracts carry little basis risk for large insurers.[4] Bantwal and Kunreuther (2000) examine the role of ambiguity aversion, loss aversion, and uncertainty avoidance in possibly deterring individual investors from investing in catastrophe bonds. Diekmann (2008) argues that catastrophe bonds' yield above the risk-free rate can be attributed to the negative shock to consumption that ensues from a large catastrophe. Barrieu and Loubergé (2009) argue that the use of catastrophe bonds can be made more attractive by protecting bond buyers against the simultaneous occurrence of a catastrophe and a market crash. Cummins and Trainar (2009) argue that catastrophe bonds are most appropriate for large, correlated risks that may endanger reinsurer solvency. Finken and Laux (2009) argue that the information-insensitive triggers often used in catastrophe bonds have adverse selection as well as moral hazard benefits. We believe our work complements existing work in that it analyzes an important yet hitherto little studied problem, that of information provision. We provide evidence of information provision in Section 3.1.

Insofar as it views reinsurance as an institution that serves to economize on information production costs, our paper is related to the extensive literature on financial intermediaries as producers of information.[5] Our paper extends this literature by considering the roles of variable costs and of information redundancy. As argued above, and as will be shown below, these play an important role in determining the preferred form of risk transfer.

Ours is not the first paper to analyze the possibly detrimental consequences of the Hirshleifer Effect for financial markets. Marin and Rahi (2000) show that the Hirshleifer Effect may deter the introduction of new securities in otherwise incomplete markets: the additional information revealed by the new securities may preclude valuable risk-sharing opportunities; such detrimental effect of new information may negate its beneficial effect, that of decreasing adverse selection. There is no such effect in our model, because risk is transferred on terms determined before the reinsurer and informed traders acquire information that might

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[4]Basis risk may, however, have been responsible for the demise of some early standardized contracts; see Cummins (2008) for further discussion.

[5]This literature can be said to have originated with Diamond's (1984) work on banks as delegated monitors. For a nice survey of financial intermediation, see Gorton and Winton (2003).

otherwise preclude such transfer. Instead, much of the costly information produced in financial markets has little social value: it is intended more to identify profitable trades than to guide capital allocation decisions; it is an instance of what Hirshleifer (1971) refers to as 'foreknowledge.'

3   The Model

We consider an insurer that has insured losses represented by an asset of a random (negative) value. The insurer has to choose between reinsuring and securitizing risk.[6] We assume that the insurer cedes a fraction $\bar{\tau}$ of the losses he has insured: $0 < \bar{\tau} < 1$.

As noted in the Introduction, the insurer wishes to transfer risk for two reasons: one is to take advantage of the reinsurer or the financial market's lower cost of capital, the other is to induce the reinsurer or traders in the financial market to produce information that will supplement the insurer's own information. The reinsurer produces information in order to economize on costly capital; traders in the financial market produce information in order to profit from trading with liquidity traders. The information produced is communicated to the insurer either directly by the reinsurer or indirectly through the price in the financial market. The insurer can then make use of this information in order to decrease the level of costly capital he himself must hold. The cost of the information produced ultimately is borne by the insurer, either directly through the reinsurance premium or indirectly through a discount on the price of the securities issued in the financial market. The purpose of the discount is to compensate liquidity traders for the losses they will sustain to informed traders. Liquidity traders' losses equal the informed traders' gross profits; these in turn equal the cost of information production.[7]

When selecting the form of risk transfer, the insurer therefore takes the difference in the cost of capital of both options into account and trades off the quality of the information obtained (which results in lower required capital) against its cost.

The remainder of the present section proceeds as follows. Section 3.1 justifies the main

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[6]Although we consider the problem faced by a primary insurer for concreteness, the analysis is identical for a reinsurer choosing between retrocession and securitization, or for a firm choosing between insurance and securitization.

[7]We shall generally specify whether a trader is informed or a liquidity trader. Where we do not, 'trader' should be understood to mean 'informed trader;' omitting the adjective sometimes lightens the exposition.

assumptions; Section 3.2 describes the underlying information structure; Section 3.3 considers the case in which only the reinsurer and traders in the financial market but not the insurer can produce information; Section 3.4 extends the analysis to the case in which the insurer too can produce information. The latter two sections provide the basis for the comparison of reinsurance and securitization in Sections 4 and 5.

3.1   Main Assumptions

Our analysis makes a number of assumptions: that it is possible to obtain information about natural catastrophe risk, that reinsurance is at least partially motivated by the desire on the part of insurers to obtain reinsurers' information about that risk, and that insurers infer information about that risk from the prices at which catastrophe instruments trade in financial markets. How justified are these assumptions?

The informational role of reinsurance is well established: In his magnum opus on reinsurance, Carter (1983, p. 10) lists 'the provision of management and technical services' among the 'purposes of reinsurance.' Carter (p. 54) describes how 'a large reinsurer might be able to draw on its own experience and knowledge of a particular class of insurance to comment on rating schedules or policy conditions proposed by a ceding company.' Specifically, 'companies writing substantial reinsurance accounts . . . provide considerable assistance to small companies in the management of their business . . . Not infrequently, a member of the reinsurer's . . . own staff will spend some time at the office of a ceding company to help in setting up management systems, devising schemes for transacting new classes of insurance, arranging suitable reinsurance programmes, and generally guiding a new company in the conduct of business.' Catastrophe risk may be considered a new or at least changing class of insurance. Mayers and Smith (1990, p. 23) write that 'reinsurance firms regularly provide a set of services to ceding insurance companies. The reinsurer frequently has broader experience with low probability events and provides information on pricing and claims adjustment services in particular areas.' Mayers and Smith examine the determinants of reinsurance purchases for a sample of 1,276 property/casualty insurance companies; they find that geographically concentrated insurers purchase less reinsurance than do their geographically diversified counterparts. Mayers and Smith ascribe this finding to the geographically concentrated insurers' lesser need for information: insurers active in few markets likely know their markets better

than insurers active in many markets know theirs. The need for information appears to dominate considerations such as taxes and bankruptcy costs, which should be exacerbated by the geographically concentrated insurers' presumably more volatile cash flows. As Mayers and Smith (p. 38) write, 'the real-service efficiency argument (which implies a negative coefficient) is quantitatively more important than the sum of the other effects through taxes, expected bankruptcy costs, and investment incentives (which all imply positive coefficients).'

Is it possible to obtain information about natural catastrophe risk? In a private communication, a member of the risk management department of a large reinsurance company describes the relation between improvements in a given catastrophe's Loss Frequency Curve (LFC) and the number of additional employees analyzing the catastrophe, expressed as Full-Time Equivalents (FTE):

> *...10% improvement with one additional FTE after 12 months (deeper understanding of model and issues); next 5% with another 1.5 FTEs after another 15 months (research in specific areas); next 2.5% with another 2 FTEs after another 18 months (strengthening of overall risk management processes); last 2.5% with another 3 FTEs after another 24 months (optimizing the remaining details and handling increased complexity).*

Roll (1984, p. 879) finds 'a statistically significant relation ... between orange juice returns and subsequent errors in temperature forecasts issued by the National Weather Service for the central Florida region where most oranges are grown.' The relation is strongest for season-weighted PM observations: orange juice returns add most to winter evening temperature forecasts, that is, to forecasts that pertain to those periods of day and year during which freezes may occur; freezes that last more than a few hours kill trees and damage crops. We interpret both the statement made by the risk manager of the large reinsurance company and the findings of Roll as evidence that reinsurers and traders in financial markets can obtain information about natural catastrophe risk.[8]

Do insurers infer information about natural catastrophe risk from the prices at which catastrophe instruments trade in financial markets? We are not aware of any evidence

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[8]It is clearly easier to obtain information about some catastrophes than about others. Catastrophes differ in how likely they are to occur and in what damages would be if a catastrophe were in fact to occur. For some catastrophes such as earthquakes, little can be known about the former; much can nonetheless be known about the latter.

bearing on this question as such. There is, however, extensive evidence that managers make use of stock price information to guide investment decisions (Barro, 1990; Durnev, Morck, and Yeung, 2004; Chen, Goldstein, and Wang, 2007). Furthermore, the more informative are stock prices, the more efficient are investment decisions, in the sense that firms that have more informative stock prices have marginal Q's closer to optimal (Durnev et al.; Chen et al.).[9] We have no reason to believe that what is true of stock price information and investment should not be true of catastrophe instrument information and capital.

3.2 The Information Structure

We represent insured losses by an asset of value $l + \delta$, with $l \sim N\left(\bar{l}, v_l\right)$, $\delta \sim N\left(0, v_\delta\right)$, $\bar{l} < 0$ and $\text{cov}\left(l, \delta\right) = 0$. An agent s, whether an insurer i, a reinsurer r, or an informed trader n, $n = 1, \ldots, N$, can acquire information

$$i_s = \delta + \sqrt{v_s}\left(\gamma\xi + \sqrt{1 - \gamma^2}\epsilon_s\right), \quad 0 \leqslant \gamma \leqslant 1 \tag{1}$$

We assume $\xi \sim N\left(0, 1\right)$, $\epsilon_s \sim N\left(0, 1\right)$, $\text{cov}\left(l, \xi\right) = \text{cov}\left(l, \epsilon_s\right) = \text{cov}\left(\delta, \xi\right) = \text{cov}\left(\delta, \epsilon_s\right) = \text{cov}\left(\xi, \epsilon_s\right) = \text{cov}\left(\epsilon_s, \epsilon_t\right) = 0$ for $s \neq t$, $s, t \in \{i, r, n\}$; v_s is the variance of the error term in the information. Note that the information acquired pertains exclusively to δ; no information can be acquired about l; this ensures that the uncertainty about losses can be no lower than v_l.

The error in the information about δ consists of two parts, one perfectly correlated across agents, ξ, and the other perfectly uncorrelated, ϵ_s. Any level of correlation between the error terms of two agents can therefore be obtained by varying the parameter γ. Indeed, we have

$$\text{corr}\left(i_s - \delta, i_t - \delta\right) = \text{corr}\left(\gamma\xi + \sqrt{1 - \gamma^2}\epsilon_s, \gamma\xi + \sqrt{1 - \gamma^2}\epsilon_t\right) = \gamma^2 \tag{2}$$

We refer to γ as the degree of redundancy in the information acquired. Where $\gamma = 1$, there is no difference whatsoever between one piece of information and the next, there is no value to aggregating information; all information is redundant beyond a single piece of information.[10]

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[9]The optimal marginal Q is not necessarily 1, because of financing and other constraints.

[10]On an informal level, redundancy in information captures the extent of "thinking alike" that fund manager Peter Lynch refers to in his famous observation about Wall Streeters going to the same cocktail parties and, as a result, all thinking alike so that prices cannot really be efficient. We thank Charles Cuny for suggesting this analogy to us.

As γ decreases below one, there is a value to aggregation in that aggregation decreases the overall error in the information; information beyond a single piece of information is no longer redundant.

Formally, consider the average error across N informed agents, $\frac{1}{N} \sum_{n=1}^{N} \sqrt{v_n} \left[\gamma \xi + \sqrt{1 - \gamma^2} \epsilon_n \right]$. If $v_n = v$ for all n, its variance is

$$
\begin{aligned}
\text{var} \left[\frac{1}{N} \sum_{n=1}^{N} \sqrt{v_n} \left[\gamma \xi + \sqrt{1 - \gamma^2} \epsilon_n \right] \right] &= v \left[\frac{\gamma^2}{N^2} \text{var} \left[\sum_{n=1}^{N} \xi \right] + \frac{1 - \gamma^2}{N^2} \text{var} \left[\sum_{n=1}^{N} \epsilon_n \right] \right] \\
&= v \left(\gamma^2 + \frac{1 - \gamma^2}{N} \right)
\end{aligned}
\tag{3}
$$

Using that variance as a proxy for the uncertainty about δ that remains once the information across all agents has been aggregated, we see that there is no decrease in uncertainty where $\gamma = 1$. In contrast, uncertainty decreases in N where $\gamma < 1$. Our presumption is that less well-understood risks are those with high γ: aggregation does little to decrease overall uncertainty about those risks. In contrast, risks that are well-understood in the aggregate should have low γ: aggregation is effective at reducing overall uncertainty about these risks.[11] We show in Sections 4 and 5 that redundancy in the information about natural catastrophe risk affects the choice between reinsurance and securitization.

We allow v_s to be chosen by agent s and assume that the agent's information acquisition cost consists of a fixed and a variable component. By incurring a fixed cost of k, agent s can acquire a signal with error variance $v_s = \overline{v}$, i.e., $1/\overline{v}$ is the minimum precision of the information that can be acquired. The agent can then improve his understanding of the risk, i.e., refine the quality of his information by decreasing the variance of the error term to $v_s < \overline{v}$, at a variable cost $c_s (\overline{v}/v_s - 1)$. The agent's total cost of acquiring information is therefore $c_s (\overline{v}/v_s - 1) + k$.[12] Note that information acquisition by agent s decreases the variance of the entire error term, reducing both correlated and uncorrelated errors, in the same proportion.

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[11] These are the risks for which prediction markets are likely to be effective. For a nice survey of prediction markets, see Wolfers and Zitzewitz (2004).

[12] As in Subrahmanyam and Titman (1999; p. 1060), and in the line of Grossman and Stiglitz (1980), we assume that each agent acquires a single signal. This being said, the ability of each agent to improve the quality of his information by decreasing v_s is equivalent to allowing him to obtain additional signals, each with variance $\overline{v}$. In the special case where the error terms of the individual signals are independent, our formulation reduces to assuming that the first signal costs k and each subsequent signal c_s. We choose the formulation $c_s (\overline{v}/v_s - 1) + k$ for tractability.

We assume that $c_r = c_n \equiv c$ and distinguish between the two cases where i) c_i is infinite and ii) c_i is finite. We wish to provide neither the reinsurer nor traders in the financial market with an advantage over the other;[13] furthermore, we wish to examine separately the case of an insurer that cannot acquire information and that of an insurer that can.[14]

3.3 The Insurer Cannot Acquire Information

We solve for informed traders' optimal information gathering decision in Section 3.3.1 and for the reinsurer's in Section 3.3.2; we derive the insurer's payoffs for both risk transfer mechanisms in Section 3.3.3.

3.3.1 The Financial Market

In this section, we describe the structure of the financial market that we consider and investigate information acquisition if the insurer decides to transfer risk by issuing catastrophe instruments with aggregate payoff $\overline{\tau}(l + \delta)$ on the financial market.[15] The structure we use closely follows Subrahmanyam and Titman (1999), who generalize Kyle (1985). In the primary market, all securities are purchased by liquidity traders.[16] The secondary market consists of N informed traders and of the liquidity traders who purchased the security in the primary market. The N informed traders base their demand on the information they acquire. The liquidity traders have demand z uncorrelated with all other variables, $z \sim N(0, v_z)$. Prices in the secondary market are set by a competitive risk-neutral market maker who expects to earn zero profit conditional on his information set. We are interested in determining the number of traders that choose to become informed, N, the precision of the information they choose to acquire, $1/v$, the information reflected in the price, and the price at which the securities are issued in the primary market. As in Holmström and Tirole (1993), this price is such that liquidity traders break even in expectation, accounting for the

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[13]The assumption $c_r = c_n$ may be considered a bias against reinsurance; specialization arguably makes $c_r < c_n$.

[14]An alternative formulation would distinguish between the two cases k_i infinite and k_i finite. We choose to distinguish between variable rather than fixed costs because our interest extends beyond the question of 'whether the insurer produces information' to 'how much information the insurer produces.'

[15]Note that we do not consider the problem of optimally designing these securities. For an analysis of optimal security design, see for example Boot and Thakor (1993), DeMarzo and Duffie (1999), and Fulghieri and Lukin (2001).

[16]We follow Holmström and Tirole (1993) and Subrahmanyam and Titman (1999) in making this simplifying assumption.

losses they expect to sustain to informed traders in the secondary market.

Recall that an informed trader n receives information $i_n = \delta + \sqrt{v_n}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_n\right)$, where δ is the uncertain amount of the loss. We conjecture an equilibrium in which trader n submits an order of the form $x_n = \kappa_n i_n$ and the market maker sets a price $P = \overline{\tau}\overline{l} + E\left[\overline{\tau}\delta\,|Q\right] = \overline{\tau}\overline{l} + \zeta Q$, where ζ denotes the price impact of order flow and

$$Q = x_n + \sum_{\substack{m=1 \\ m\neq n}}^{N} \kappa i_m + z = x_n + \sum_{\substack{m=1 \\ m\neq n}}^{N} \kappa\left(\delta + \sqrt{v}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_m\right)\right) + z \tag{4}$$

denotes the total order flow received by the market maker, including liquidity trader demand z. The market maker cannot distinguish between liquidity and informed trader demand. Note that we consider a symmetric equilibrium, in which κ and v are the same for all informed traders.

Trader n takes the demand and the (inverse) quality of the information of the other informed traders as given when choosing his own demand x_n and his (inverse) quality of information v_n. Hence, in choosing x_n, trader n solves

$$\max_{x_n} E\left[x_n\left[\overline{\tau}l + \overline{\tau}\delta - P\right]|i_n\right] \equiv \max_{x_n} E\left[x_n\left[\overline{\tau}\delta - \zeta Q\right]|i_n\right] \tag{5}$$

$$\equiv \max_{x_n} E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1 \\ m\neq n}}^{N} \kappa i_m + z\right)\right]|i_n\right]$$

Solving for x_n (the details are in the appendix), we have

$$x_n = \kappa_n i_n = \kappa_n\left(\delta + \sqrt{v_n}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_n\right)\right) \tag{6}$$

where
$$\kappa_n = \frac{1}{2\zeta}\frac{\overline{\tau}v_\delta - \zeta\left(N-1\right)\kappa\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)}{v_\delta + v_n} \tag{7}$$

In choosing v_n, trader n uses x_n obtained in (6) to solve

$$\max_{v_n} E\left[E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1 \\ m\neq n}}^{N} \kappa i_m + z\right)\right]|i_n\right]\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{8}$$

subject to the constraint $0 \leq v_n \leq \overline{v}$. In so doing, trader n treats κ, ζ, and v as constant.

It is interesting to compare (5) and (8): both pertain to the maximization of trading profits, the former over the choice of demand and conditional on information, the latter over the choice of information quality and unconditionally. The trader recognizes that the quality of the information he acquires (8) affects the level of trading profits he can expect to make (5).

We show in the appendix that in a symmetric equilibrium ($v_n = v$), we have

$$\zeta = \frac{\overline{\tau} v_\delta \sqrt{N(v_\delta + v)}}{\sqrt{v_z}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]} \tag{9}$$

$$\kappa = \sqrt{\frac{v_z}{N(v_\delta + v)}} \tag{10}$$

and that the first-order condition for v is

$$\frac{\overline{\tau}(2 + (N-1)\gamma^2)\sqrt{v_z}v_\delta}{2\sqrt{N}\sqrt{v_\delta + v}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]} = c\frac{\overline{v}}{v^2} \tag{11}$$

Consider first the price impact of order flow, ζ in (9). The larger liquidity trading variance, v_z, the greater the importance of liquidity trader demand in order flow, and the lower therefore the price impact of order flow. The greater information redundancy, γ, the more intense the competition between informed traders, and the lesser therefore the price impact. The larger the number of informed traders, N, the more intense the competition between them; the larger also the pool of information in the order flow. The former effect decreases ζ; the latter increases it. Which effect dominates depends on N: when $N > N^* \equiv 1 + 2(1-\gamma^2)v/(v_\delta + \gamma^2 v)$, the competition effect dominates and ζ decreases in N; the opposite is true when $N < N^*$.[17] The greater the variance of losses v_δ, the more the market maker stands to lose, and the greater therefore the price impact of order flow.[18]

This last effect is reflected in the aggressiveness with which informed traders respond to information, κ in (10): foreseeing the large price impact of order flow, informed traders submit small orders when v_δ is large. In contrast, informed traders respond more aggressively

---

[17]Note that N^* decreases in γ: the more correlated traders' information, the smaller the number of traders required for the competition effect to dominate.

[18]The effect of v on ζ is ambiguous, since

$$\frac{\partial}{\partial v}\left(\frac{\sqrt{v_\delta + v}}{(N+1)v_\delta + (2 + (N-1)\gamma^2)v}\right) = \frac{((N-3) - 2(N-1)\gamma^2)v_\delta - (2 + (N-1)\gamma^2)v}{2\sqrt{v_\delta + v}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]^2}$$

to information, the greater the "camouflage" they are afforded by liquidity traders (large v_z), the lesser the competition between informed traders (small N), and the higher the quality of their information (low v).

Now consider the first-order condition (11). Greater liquidity trading variance, v_z, increases information acquisition in the financial market; as already noted, liquidity trading provides informed traders with the means to "camouflage" the trades they carry out in order to profit from the information they acquire. Greater information redundancy, γ, also increases information acquisition.[19] To understand why, note that two properties of information make it valuable: its quality (low v), and its uniqueness (low γ). An informed trader responds to a decrease in the uniqueness of the information (higher γ) by increasing its quality (lower v) in an attempt to maintain its trading profits. A larger number of traders N reduces information acquisition because competition erodes trading profits.[20] Note also that since the left hand side of (11) tends to zero as N becomes large, no trader will incur the cost of improving the quality of his information beyond $1/\overline{v}$ in a financial market with a large number of informed traders: competition between traders drives the trader's expected profit to zero, thereby precluding him from recovering any cost he may have incurred and deterring him from incurring that cost in the first place. Finally, the quality of the information acquired, $1/v$, is increasing in the fraction of risk transferred, $\overline{\tau}$, and in the starting quality of the information, $1/\overline{v}$: more at stake induces more information acquisition; information acquisition is impeded by lower quality starting information.[21]

---

[19]To see this, note that

$$\frac{\partial}{\partial(\gamma^2)}\left(\frac{2+(N-1)\gamma^2}{(N+1)v_\delta+(2+(N-1)\gamma^2)v}\right)=\frac{\left(N^2-1\right)v_\delta}{[(N+1)v_\delta+(2+(N-1)\gamma^2)v]^2}>0$$

[20]To see this, note that

$$\frac{\partial}{\partial N}\left(\frac{2+(N-1)\gamma^2}{\sqrt{N}\,[(N+1)v_\delta+(2+(N-1)\gamma^2)v]}\right)$$

$$=\quad-\frac{\left((2-\gamma^2)+(6-4\gamma^2)N+N^2\gamma^2\right)v_\delta+\left(2+(N-1)\gamma^2\right)^2v}{2N^{\frac{3}{2}}\,[(N+1)v_\delta+(2+(N-1)\gamma^2)v]^2}<0$$

[21]The impact of v_δ on v is ambiguous, since

$$\frac{\partial}{\partial v_\delta}\left(\frac{v_\delta}{\sqrt{v_\delta+v}\,[(N+1)v_\delta+(2+(N-1)\gamma^2)v]}\right)=\frac{\left(2+(N-1)\gamma^2\right)v\left(v_\delta+2v\right)-(N+1)v_\delta^2}{2\left(v_\delta+v\right)^{\frac{3}{2}}[(N+1)v_\delta+(2+(N-1)\gamma^2)v]^2}$$

14

As shown in the appendix, the expected profit of an informed trader is

$$\Pi_f = \frac{\overline{\tau}\sqrt{v_z}v_\delta\sqrt{v_\delta + v}}{\sqrt{N}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]} - c\left(\frac{\overline{v}}{v} - 1\right) - k \tag{12}$$

As one would expect, this profit is increasing in the fraction of risk transferred, $\overline{\tau}$, in the variance of liquidity trader demand, v_z, in the starting quality of information, $1/\overline{v}$, and in the uncertainty about the loss δ, v_δ.[22] It is decreasing in the number of traders N, in the fixed and variable costs of information acquisition, k and c, and in the degree of information redundancy, γ. This last effect arises because—as is well-known from the auction literature (Milgrom and Weber, 1982)—traders earn larger profits when the information available to them has a larger idiosyncratic error component. When γ is large, the idiosyncratic error component is small.

In equilibrium, the number of informed traders N active in the market is such that $\Pi_f(N) = 0$. Given the properties of Π_f, the equilibrium number of traders is larger, the higher $\overline{\tau}$, v_z and v_δ, and the smaller $\overline{v}$, c, k and γ. The information contained in the price at equilibrium is that contained in the total order flow Q, as $P = \overline{\tau}\overline{l} + \zeta Q$. This information is

$$Q = \kappa\sum_{n=1}^{N} i_n + z = N\kappa\left(\delta + \sqrt{v}\gamma\xi\right) + \kappa\sqrt{v}\sqrt{1-\gamma^2}\sum_{n=1}^{N}\epsilon_n + z \tag{13}$$

The securities are issued in the primary market at a discount to their expected value, $\overline{\tau}\overline{l}$. The discount serves to compensate liquidity traders for the losses they expect to sustain to informed traders in the secondary market. The discount is endogenous and equals total information acquisition costs, $N(c(\overline{v}/v - 1) + k)$.[23] The issue price therefore equals

$$I \equiv \overline{\tau}\overline{l} - N\left(c\left(\frac{\overline{v}}{v} - 1\right) + k\right) \tag{14}$$

As $\overline{l}$ is negative, $I < 0$: liquidity traders are paid to bear a fraction $\overline{\tau}$ of the losses.

---

[22]We have

$$\frac{\partial}{\partial v_\delta}\left(\frac{v_\delta\sqrt{v_\delta + v}}{(N+1)v_\delta + (2 + (N-1)\gamma^2)v}\right) = \frac{(N+1)v_\delta^2 + \left(2 + (N-1)\gamma^2\right)v\left(3v_\delta + 2v\right)}{2\sqrt{v_\delta + v}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)\right]^2} > 0$$

[23]Liquidity traders' expected losses equal $E((P - \overline{\tau}(l + \delta))z) = E(\zeta Q z) = \zeta v_z$. Using (9) and $\Pi_f(N) = 0$, we have

$$\zeta v_z = \sqrt{v_z}\frac{\overline{\tau}v_\delta\sqrt{N(v_\delta + v)}}{(N+1)v_\delta + (2 + (N-1)\gamma^2)v} = N\left(c\left(\frac{\overline{v}}{v} - 1\right) + k\right)$$

3.3.2 The Reinsurer

In this section, we investigate information acquisition if the insurer decides to transfer risk to the reinsurer. Let the reinsurer r have net cost of capital a_r. Capital is needed by the reinsurer to maintain solvability in the face of greater than expected losses. We assume that for each unit of risk remaining (as measured by the standard deviation of losses after the reinsurer has acquired any additional information on the loss he deems desirable), the reinsurer requires λ units of capital. A higher λ may reflect more stringent capital requirements or greater covariability of the loss with the reinsurer's existing book (Froot and Stein, 1998; Zanjani, 2002; Froot, 2007).

The reinsurer's capital has positive net cost because of information and incentive considerations that create a wedge between the internal and external costs of capital (Froot, Scharfstein, and Stein, 1993; Froot and O'Connell, 1997; Gron and Winton, 2001). While such wedge exists in the financial market too, it is much lower in that case: considerations of information and incentives apply much more to capital invested in the shares of reinsurance companies than deposited as margin requirement (for exchanges) or lent as principal (for catastrophe bonds). For simplicity, we have assumed the net cost of capital in the financial market to be zero.

Diversification within the reinsurance company makes any discount at which the reinsurer issues shares much smaller than the discount on the catastrophe instruments considered in Section 3.3.1. This is the direct analogue to Subrahmanyam (1991) and Gorton and Pennacchi's (1993) comparison of individual stocks and stock market indices: the opportunities for informed traders to profit from their private information are much more limited where trading a claim on a widely diversified portfolio of catastrophe and other risks—reinsurance company shares—than a claim on a single catastrophe.[24] For simplicity, we assume the discount on reinsurance company shares to be zero.[25]

As mentioned in Section 3.2, the reinsurer can acquire the same information as an informed trader, at the same cost. The problem solved by the reinsurer who reinsures a fraction

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[24]The bundling of different catastrophe risks within a single catastrophe instrument would reduce but not eliminate the difference in discounts, because of reinsurance companies' much more extensive diversification.

[25]Neither simplifying assumption is essential for our results; the two assumptions dramatically simplify our analysis.

$\overline{\tau}$ of insured losses $l + \delta$ is

$$\max_{v_r} \overline{\tau} \left(\overline{l} - \lambda a_r SD \left[l + \delta \, \middle| \, \delta + \sqrt{v_r} \left(\gamma \xi + \sqrt{1 - \gamma^2} \epsilon_r \right) \right] \right) - c \left(\frac{\overline{v}}{v_r} - 1 \right) - k$$

$$= \max_{v_r} \overline{\tau} \left(\overline{l} - \lambda a_r \left[v_l + \frac{v_\delta v_r}{v_\delta + v_r} \right]^{\frac{1}{2}} \right) - c \left(\frac{\overline{v}}{v_r} - 1 \right) - k \tag{15}$$

where $SD[\cdot]$ denotes the standard deviation of losses after incorporating any information acquired, subject to the constraint $0 \leq v_r \leq \overline{v}$. Note that the amount of capital needed, as represented by λ times the conditional standard deviation, is decreasing in the quality of the information acquired, $1/v_r$: higher quality information decreases loss uncertainty, thereby decreasing the need for capital.

In the case of an interior solution, problem (15) has first-order condition

$$\frac{\overline{\tau} \lambda a_r}{2} \frac{v_\delta^2}{(v_\delta + v_r)^{\frac{3}{2}} (v_\delta v_r + v_\delta v_l + v_l v_r)^{\frac{1}{2}}} = c \frac{\overline{v}}{v_r^2} \tag{16}$$

The preceding equation can be rewritten as

$$\frac{v_\delta v_r^{\,2}}{(v_\delta + v_r)^{\frac{3}{2}} (v_\delta v_r + v_\delta v_l + v_l v_r)^{\frac{1}{2}}} = \phi, \quad \phi \equiv \frac{2c\overline{v}}{\overline{\tau} \lambda a_r} \tag{17}$$

The quality of the information acquired, $1/v_r$, is increasing in v_δ and decreasing in v_l.[26] There is a difference between the manner in which the reinsurer reacts to an increase in uncertainty regarding losses about which he cannot acquire information (v_l) and those about which he can (v_δ). The reinsurer acquires higher quality information in response to an increase in the latter, thereby offsetting at least part of the increased uncertainty; he acquires lower quality information in response to an increase in the former, for such increase makes any information he may acquire less valuable.

Since there is a single reinsurer, the degree of information redundancy γ has no impact on the reinsurer's optimal information acquisition strategy. Since v_r is increasing in ϕ, a greater

---

[26]To see this, note that

$$\frac{\partial v_r}{\partial v_l} = \frac{v_r}{2 (v_\delta + v_r)^2 \left(2v_l (v_\delta + v_r) + \frac{3}{2} v_\delta v_r \right) v_\delta} > 0$$

and

$$\frac{\partial v_r}{\partial v_\delta} = -\frac{v_r^2}{v_\delta^2} < 0$$

net cost of capital, a_r, and more stringent capital requirements, λ, induce more information acquisition by the reinsurer, as higher quality information serves to economize on costly capital.[27] Finally, as in the case of the financial market, the quality of the information acquired, $1/v_r$, is increasing in the fraction of risk transferred, $\overline{\tau}$, and in the starting quality of the information, $1/\overline{v}$.

It is instructive to compare v_r in (17) with v in (11). Unlike v_r, v does not depend on v_l; v depends only on v_δ: informed traders in the financial market are concerned only with that part of losses about which they can acquire information, for only such part provides these traders with profitable trading opportunities. It is possible to have both $v_r > v$ and $v_r < v$. To obtain the former, increase v_z and concurrently increase k to keep N constant. For v_z large enough, there will be a $v < v_r$. To obtain the latter, let k be so small and therefore N so large as to make $v = \overline{v}$. For large a_r, v_r will be less than $\overline{v}$ and therefore less than v.

3.3.3 The Insurer

Having analyzed the information gathering incentives of informed traders in the financial market and of the reinsurer, we can now determine the expected cost to the insurer of using the financial market or reinsurance to transfer risk. We do not allow the insurer simultaneously to securitize in the financial market and to reinsure: the separate examination of each form of risk transfer makes for clearer understanding and starker comparison.

From (14), the expected cost to the insurer of ceding a fraction $\overline{\tau}$ of the losses to the financial market is that fraction of the expected loss $\overline{l}$ plus the combined cost of information acquisition by informed traders, $I = \overline{\tau}\overline{l} - N\left(c\left(\overline{v}/v - 1\right) + k\right)$. The benefit is a reduction in the required amount of capital arising from the fact that the insurer only retains a fraction $1 - \overline{\tau}$ of the risk, and from the improved quality of the information. Hence, letting a_i denote the insurer's cost of capital and assuming, as for the reinsurer, that the insurer must hold λ units of capital for each unit of risk remaining, the insurer's expected payoff from using the

---

[27]To see this, note that

$$\frac{\partial v_r}{\partial \phi} = \frac{\left(v_l v_\delta + v_l v_r + v_\delta v_r\right)^{\frac{3}{2}}}{\left(v_\delta + v_r\right)^2 \left(2 v_l \left(v_\delta + v_r\right) + \frac{3}{2} v_\delta v_r\right) v_\delta^3 v_r} > 0$$

financial market for transferring risk is

$$\Gamma_{i,f} = (1-\overline{\tau})\,\overline{l} - \lambda a_i\,(1-\overline{\tau})\,SD\,[l+\delta\,|Q] + \overline{\tau}\overline{l} - N\left(c\left(\frac{\overline{v}}{v}-1\right)+k\right) \tag{18}$$

$$= \overline{l} - \lambda a_i\,(1-\overline{\tau})\left[v_l + \frac{v_\delta^2 + (2+(N-1)\gamma^2)\,v_\delta v}{(N+1)v_\delta + (2+(N-1)\gamma^2)\,v}\right]^{\frac{1}{2}} - N\left(c\left(\frac{\overline{v}}{v}-1\right)+k\right)$$

where the second equality follows from (10) and (13), v is the solution to (11), and N is obtained from the zero profit condition $\Pi_f(N) = 0$. Note that the price is more informative ($SD[l+\delta|Q]$ is smaller), the larger the number of traders, N, the higher the quality of their information, $1/v$, and the lower the degree of redundancy in the information produced, γ. The variance of liquidity trader demand, v_z, has no direct impact on price informativeness, but has an indirect effect through its impact on the equilibrium number of traders N and the quality of the information they acquire $1/v$.

Similarly, the expected cost to the insurer of ceding a fraction $\overline{\tau}$ of the losses to the reinsurer is that fraction of the expected loss $\overline{l}$, plus the reinsurer's capital cost, plus his information acquisition cost, i.e., $\overline{\tau}\overline{l} - \lambda a_r \overline{\tau} SD\,[\delta\,|i_r] - c\,(\overline{v}/v_r - 1) - k$. The benefit is again a reduction in the required amount of capital. Hence, the insurer's expected payoff from transferring risk to the reinsurer is

$$\Gamma_{i,r} = (1-\overline{\tau})\,\overline{l} - \lambda a_i\,(1-\overline{\tau})\,SD\,[l+\delta\,|i_r] + \overline{\tau}\overline{l} - \lambda a_r\overline{\tau} SD\,[l+\delta\,|i_r] - c\left(\frac{\overline{v}}{v_r}-1\right) - k$$

$$= \overline{l} - \lambda\,[a_i\,(1-\overline{\tau}) + a_r\overline{\tau}]\left[v_l + \frac{v_\delta v_r}{v_\delta + v_r}\right]^{\frac{1}{2}} - c\left(\frac{\overline{v}}{v_r}-1\right) - k \tag{19}$$

where v_r is given by (17).

3.4 The Insurer Can Acquire Information

We now consider the case in which the insurer too can acquire information. We assume the insurer acquires information before either the reinsurer or traders in the financial market have done so; the insurer communicates this information to the reinsurer or makes it public in the process of issuing the securities in the financial market; the reinsurer or traders in the financial market then make use of the information communicated to them in deciding how

much information themselves to acquire.[28]

We assume that the insurer communicates the information he has acquired not as such but embedded into the uncertainty about losses. Specifically, the information i_i is communicated through the reduction of the variance of the part of losses δ from v_δ to $v_{\delta|i} \equiv v_\delta v_i/(v_\delta + v_i) < v_\delta$. It is on the basis of this reduced uncertainty about δ that the reinsurer and traders in the financial market now base their information acquisition and entry decisions.[29] This assumption allows us to use the results of sections 3.3.1 and 3.3.2, with the single difference that $v_{\delta|i}$ replaces v_δ. We therefore have

$$
\begin{aligned}
\Gamma_{i,f} &= \bar{l} - \lambda a_i (1 - \bar{\tau}) \left[v_l + \frac{v_{\delta|i}^2 + (2 + (N-1)\gamma^2) v_{\delta|i} v}{(N+1)v_\delta + (2 + (N-1)\gamma^2) v} \right]^{\frac{1}{2}} \\
&\quad - N \left(c \left(\frac{\bar{v}}{v} - 1 \right) + k \right) - \left(c_i \left(\frac{\bar{v}}{v_i} - 1 \right) + k \right)
\end{aligned}
$$

and

$$
\begin{aligned}
\Gamma_{i,r} &= \bar{l} - \lambda \left[a_i (1 - \bar{\tau}) + a_r \bar{\tau} \right] \left[v_l + \frac{v_{\delta|i} v_r}{v_{\delta|i} + v_r} \right]^{\frac{1}{2}} \\
&\quad - \left(c \left(\frac{\bar{v}}{v_r} - 1 \right) + k \right) - \left(c_i \left(\frac{\bar{v}}{v_i} - 1 \right) + k \right) \tag{20}
\end{aligned}
$$

Note the additional term $-c_i (\bar{v}/v_i - 1) - k$, which reflects the insurer's own information acquisition cost. The insurer chooses v_i to maximize $\Gamma_{i,f}$ in (20) in the case risk is transferred through the financial market and $\Gamma_{i,r}$ in (20) in case it is transferred through reinsurance.

How does the insurer's production of information affect that of the reinsurer and of informed traders in the financial market? Initially consider the case of reinsurance. The (inverse) quality of the information, v_i, is the solution to

$$
\begin{aligned}
\frac{d\Gamma_{i,r}}{dv_i} &= \frac{\partial \Gamma_{i,r}}{\partial v_i} + \frac{\partial \Gamma_{i,r}}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} + \frac{\partial \Gamma_{i,r}}{\partial v_r} \frac{\partial v_r}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} = 0 \\
\Leftrightarrow \frac{\partial \Gamma_{i,r}}{\partial v_i} + \frac{\partial \Gamma_{i,r}}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} &= -\frac{\partial \Gamma_{i,r}}{\partial v_r} \frac{\partial v_r}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} \tag{21}
\end{aligned}
$$

---

[28]We assume that reputational concerns and *ex post* settling up mechanisms—retrospective rating and loss sensitive premiums—deter the insurer from strategically manipulating the information he communicates. See for example Doherty and Smetters (2005).

[29]We make this assumption in order to keep the analysis tractable. We have solved the model in the case where the insurer communicates i_i as such; the resulting expressions are too unwieldy to be of much use.

We have

$$
\begin{aligned}
\frac{\partial \Gamma_{i,r}}{\partial v_r} &= -\frac{\lambda}{2} \left[a_i \left(1 - \overline{\tau} \right) + a_r \overline{\tau} \right] \left[v_l + \frac{v_{\delta|i} v_r}{v_{\delta|i} + v_r} \right]^{-\frac{1}{2}} \frac{v_{\delta|i}^2}{\left(v_{\delta|i} + v_r \right)^2} + c \frac{\overline{v}}{v_r^2} \\
&= -\frac{\lambda}{2} a_i \left(1 - \overline{\tau} \right) \left[v_l + \frac{v_{\delta|i} v_r}{v_{\delta|i} + v_r} \right]^{-\frac{1}{2}} \frac{v_{\delta|i}^2}{\left(v_{\delta|i} + v_r \right)^2} < 0 \tag{22}
\end{aligned}
$$

where the second equality is obtained by noting that v_r solves the reinsurer's maximization problem (15), with $v_{\delta|i}$ appearing in place of v_δ. As $\partial v_r / \partial v_{\delta|i} < 0$ from footnote 26 and $\partial v_{\delta|i} / \partial v_i = v_\delta^2 / \left(v_\delta + v_i \right)^2 > 0$, we conclude that the expectation on the part of the insurer that the reinsurer too will acquire information induces the insurer to acquire lower quality information than he otherwise would (v_i is larger than it otherwise would be): the RHS of equation (21) is negative. The reinsurer, too, acquires lower quality information than he otherwise would; this is immediate from $\partial v_r / \partial v_{\delta|i} < 0$ and $v_{\delta|i} < v_\delta$. There is therefore substitutability in the insurer and the reinsurer's information acquisition decisions.

Now consider the case of the financial market. The (inverse) quality of the information, v_i, is the solution to

$$
\begin{aligned}
\frac{d\Gamma_{i,f}}{dv_i} &= \frac{\partial \Gamma_{i,f}}{\partial v_i} + \frac{\partial \Gamma_{i,f}}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} + \frac{\partial \Gamma_{i,f}}{\partial v} \frac{dv}{dv_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} + \frac{\partial \Gamma_{i,f}}{\partial N} \frac{\partial N}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} = 0 \\
\Leftrightarrow \frac{\partial \Gamma_{i,f}}{\partial v_i} + \frac{\partial \Gamma_{i,f}}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} &= -\frac{\partial \Gamma_{i,f}}{\partial v} \left(\frac{\partial v}{\partial v_{\delta|i}} + \frac{\partial v}{\partial N} \frac{\partial N}{\partial v_{\delta|i}} \right) \frac{\partial v_{\delta|i}}{\partial v_i} - \frac{\partial \Gamma_{i,f}}{\partial N} \frac{\partial N}{\partial v_{\delta|i}} \frac{\partial v_{\delta|i}}{\partial v_i} \tag{23}
\end{aligned}
$$

Unlike $\partial \Gamma_{i,r} / \partial v_r$, it is impossible to sign $\partial \Gamma_{i,f} / \partial v$; it is also impossible to sign $\partial \Gamma_{i,f} / \partial N$.[30] There is no general result regarding whether the (inverse) quality of the insurer's information is increased or decreased by the expectation that informed traders too will acquire information. Unlike the case of reinsurance, it is possible for v_i to be decreased by that expectation: an insurer who knows that informed traders will acquire information may decide himself to acquire higher quality information. The reason the insurer may do so is in order to decrease

---

[30]We have

$$
\frac{\partial \Gamma_{i,f}}{\partial v} = -\frac{\lambda}{2} a_i \left(1 - \overline{\tau} \right) \left[v_l + \frac{v_{\delta|i}^2 + \left(2 + (N-1)\gamma^2 \right) v_{\delta|i} v}{(N+1) v_{\delta|i} + \left(2 + (N-1)\gamma^2 \right) v} \right]^{-\frac{1}{2}} \frac{\left(2 + (N-1)\gamma^2 \right) N v_{\delta|i}^2}{\left((N+1) v_{\delta|i} + \left(2 + (N-1)\gamma^2 \right) v \right)^2} + Nc \frac{\overline{v}}{v^2}
$$

and

$$
\frac{\partial \Gamma_{i,f}}{\partial N} = \frac{\lambda}{2} a_i \left(1 - \overline{\tau} \right) \left[v_l + \frac{v_{\delta|i}^2 + \left(2 + (N-1)\gamma^2 \right) v_{\delta|i} v}{(N+1) v_{\delta|i} + \left(2 + (N-1)\gamma^2 \right) v} \right]^{-\frac{1}{2}} \frac{\left(v_{\delta|i} + \left(2 + \gamma^2 \right) v \right) v_{\delta|i}^2}{\left((N+1) v_{\delta|i} + \left(2 + (N-1)\gamma^2 \right) v \right)^2} - \left(c \left(\frac{\overline{v}}{v} - 1 \right) + k \right)
$$

the extent of the Hirshleifer effect: higher quality information provided by the insurer decreases entry and information acquisition by informed traders. Sufficient conditions for this to be the case are that $\partial \Gamma_{i,f}/\partial v > 0$, $dv/dv_{\delta|i} < 0$, and $\partial \Gamma_{i,f}/\partial N < 0$.[31] The first inequality indicates that informed traders acquire information of excessively high quality, in the sense that the cost of such information—the discount on the securities issued—is higher than its benefit—reduced capital requirement. The second inequality indicates that, as does the reinsurer, informed traders acquire lower quality information in response to the provision of higher quality information by the insurer. The third inequality indicates that there are too many informed traders in the financial market: the associated entry costs are higher than the benefits of more extensively aggregated information.

4 Two Polar Cases

We wish to compare $\Gamma_{i,f}$ and $\Gamma_{i,r}$ for the purpose of determining the superior form of risk transfer, that yielding the highest expected payoff to the insurer. There are no general results for this comparison, but some preliminary intuition is provided and some of the tradeoffs involved are illustrated by considering the two polar cases of $\gamma = 0$ and $\gamma = 1$. We assume i) $k = 0$ and N therefore large as well as ii) $c_i = \infty$ for simplicity.

When the number of traders is large, competition erodes trading profits, and informed traders do not acquire information beyond $1/\overline{v}$. Nevertheless, when $\gamma = 0$, there is no aggregate uncertainty about δ for large N: as the price in the financial market aggregates all information, the insurer can infer from that price the exact value of δ. We thus have

$$\Gamma_{i,f} = \bar{l} - \lambda a_i \left(1 - \overline{\tau}\right) \sqrt{v_l} \tag{24}$$

In contrast, the reinsurer is able to profit from the information he acquires, and may therefore select $v_r < \overline{v}$. The payoff to the insurer from using reinsurance is given by

$$\Gamma_{i,r} = \bar{l} - \lambda \left[a_i \left(1 - \overline{\tau}\right) + a_r \overline{\tau}\right] \left[v_l + \frac{v_\delta v_r}{v_\delta + v_r}\right]^{\frac{1}{2}} - c \left(\frac{\overline{v}}{v_r} - 1\right) \tag{25}$$

Hence, regardless of whether the reinsurer chooses to acquire information beyond $1/\overline{v}$ or

[31]Using $\partial N/\partial v_{\delta|i} > 0$ from the discussion following equation 12 and $\partial v_{\delta|i}/\partial v_i > 0$, the RHS of equation (23) is positive.

not, the insurer's payoff from using reinsurance is *lower* than that from using the financial market; securitization dominates reinsurance.

On the other hand, when $\gamma = 1$, aggregate uncertainty in the financial market remains even for large N. Since no trader acquires information beyond $1/\overline{v}$, the insurer's payoff from using the financial market is

$$\Gamma_{i,f} = \bar{l} - \lambda a_i \left(1 - \overline{\tau}\right) \left[v_l + \frac{v_\delta \overline{v}}{v_\delta + \overline{v}}\right]^{\frac{1}{2}} \tag{26}$$

The expected payoff from using reinsurance does not depend on γ, and is therefore still given by (25). Note that since the reinsurer's incentive to acquire information is smaller than the first-best level, any information the reinsurer acquires is worth more than its cost from the insurer's point of view. Thus, the insurer's profit from using reinsurance is bounded from below by (25) with $v_r = \overline{v}$, i.e., one has

$$
\begin{aligned}
\Gamma_{i,r} &= \bar{l} - \lambda \left[a_i \left(1 - \overline{\tau}\right) + a_r \overline{\tau}\right] \left[v_l + \frac{v_\delta v_r}{v_\delta + v_r}\right]^{\frac{1}{2}} - c\left(\frac{\overline{v}}{v_r} - 1\right) \\
&> \bar{l} - \lambda \left[a_i \left(1 - \overline{\tau}\right) + a_r \overline{\tau}\right] \left[v_l + \frac{v_\delta \overline{v}}{v_\delta + \overline{v}}\right]^{\frac{1}{2}}
\end{aligned} \tag{27}
$$

Thus, when $\gamma = 1$, two opposing effects operate. On the one hand, the (potentially) higher quality of the information in the case of reinsurance favors reinsurance over securitization. On the other hand, the zero net cost of capital of the financial market favors securitization over reinsurance. Which effect dominates determines the optimal form of risk transfer. It is interesting to contrast these results with those of Subrahmanyam and Titman (1999). In their model, when costly information is perfectly correlated across agents, private financing (reinsurance in our case) is *always* used because it avoids the duplication of effort in information production that arises in the financial market. In our setting, the financial market may nevertheless be used because of its lower cost of capital.

5   Determinants of the Preferred Form of Risk Transfer

In order to gain greater insights into the drivers of the preferred form of risk transfer, we solve the model numerically, computing the insurer's expected payoff from securitizing and

reinsuring risk for different parameter constellations. We first consider the case where the insurer does not acquire information in Section 5.1. In Section 5.2, we turn to the case where the insurer produces information.

5.1 The Insurer Cannot Acquire Information

Numerical Solution Methodology: The payoff from transferring risk to the financial market is obtained by first determining the optimal amount of information acquisition by each informed trader, v, using the first-order condition (11), taking the number of traders N as given. The equilibrium number of traders is then determined as the largest value of N for which the traders' expected profit (12), given their optimal information acquisition strategy v, is nonnegative. Finally, given N and v, the insurer's payoff is computed using (18). Similarly, the insurer's payoff from transferring risk to the reinsurer is obtained by first determining the reinsurer's optimal information acquisition strategy v_r using (17). The insurer's payoff is then obtained by inserting the optimal v_r into (19).

Base Case: Before analyzing the impact of the different parameters on the preferred form of risk transfer, we solve the model for parameter values computed from information obtained from Swiss Re. We view these values as loosely representing current assessment of the distribution of losses and the information about such losses for a natural catastrophe event. The values are (m denotes millions): $\bar{l} = -500m$, $\sqrt{v_l} = 500m$, $\sqrt{v_\delta} = 1,500m$, $\sqrt{\bar{v}} = 1,000m$, $\bar{\tau} = 0.5$, $k = 5m$, and $c = 6m$.[32] To help interpret the parameter c that indexes the variable cost of acquiring information, note that a value of $6m$ implies that the variable cost of halving the standard deviation of the error in the information from $\sqrt{\bar{v}} = 1,000m$ to $\sqrt{v} = 500m$ is $18m$.

We set $\lambda = 2.5$, implying that the insurer and the reinsurer hold enough capital to cover losses with a probability of slightly over 99%. Using the results of Fama and French (1997) and information provided by Swiss Re, we set $a_i = 0.06$ and $a_r = 0.05$.[33] Finally, reflecting

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[32]The fixed information acquisition cost $k = 5m$ is well above the cost of licensing even a sophisticated natural catastrophe model, for much is needed to make good use of such models. Users must improve the quality of the input data on exposures, interpret the output, sensitivity-test their results, and understand what key assumptions are in the model for certain types of underwriting decisions (Chordas, 2006).

[33]Fama and French (1997) do not provide separate figures for the reinsurance industry. Information provided by Swiss Re suggests that reinsurers have a 100bp cost of capital advantage over insurers.

the lack of trading in catastrophe derivatives, we set $\sqrt{v_z} = 1m$: liquidity traders' demand has standard deviation equal to 0.2% of expected loss.

Thus, in our base case, losses associated with catastrophes are large and highly uncertain; the fixed and variable costs of acquiring information are high; the standard deviation of liquidity trader demand is low; and acquiring information at the level $1/\overline{v}$ permits reducing the uncertainty about losses by about 40%.

The results of our base case are shown in Figure 1, which presents the model's solution as a function of the degree of information redundancy, γ. Specifically, the six panels in the figure report (1) the number of informed traders, N, (2) the (inverse) quality of the information acquired, $\sqrt{v}$ for the financial market and $\sqrt{v_r}$ for reinsurance, (3) the loss uncertainty facing the insurer once information has been acquired, $SD\left[l + \delta \,|Q\right]$ for the financial market and $SD\left[l + \delta \,|i_r\right]$ for reinsurance, (4) the total information acquisition cost, $N\left(c\left(\overline{v}/v - 1\right) + k\right)$ for the financial market and $c\left(\overline{v}/v_r - 1\right) + k$ for reinsurance, (5) the total capital cost, $\lambda a_i\left(1 - \overline{\tau}\right)SD[l + \delta|Q]$ for the financial market and $\lambda\left[a_i\left(1 - \overline{\tau}\right) + a_r\overline{\tau}\right]SD[l + \delta|i_r]$ for reinsurance, and (6) the payoffs to the insurer from both forms of risk transfer, $\Gamma_{i,f}$ and $\Gamma_{i,r}$.

Figure 1 reveals that reinsurance dominates the financial market for all values of γ. The reason is that the financial market's capital cost advantage is not sufficient to offset its information cost disadvantage. The large information cost disadvantage arises from the combination of the large fixed information acquisition cost of $5m$ and the large number of traders (between 15 and 30 depending on γ) that choose to become informed in the financial market, resulting in total information acquisition costs of about $150m$ (versus about $10m$ for reinsurance). The financial market's capital cost advantage, which ranges from about $70m$ for $\gamma = 0$ to about $40m$ for $\gamma = 1$, represents the net impact of two effects. First, the capital cost for the part of risk transferred is zero for the financial market and a_r for reinsurance; this first effect unambiguously favors the financial market. Second, the quality of the information produced affects the amount of costly capital that the insurer must hold. Note that except for very large values of γ, the reinsurer acquires more precise information than individual informed traders in the financial market. Nonetheless, for $\gamma < 0.7$, information acquisition by multiple traders yields better quality information than reinsurance, allowing the insurer to hold less capital than he would with reinsurance. When the degree of redundancy in the information produced is large ($\gamma > 0.7$), the opposite holds.

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It is instructive to consider the impact of the degree of information redundancy γ. Although γ does not affect the reinsurer's information acquisition strategy and the cost of using reinsurance (see Section 3), it does affect information production in the financial market. As γ increases, the number of traders decreases (because expected profit per trader falls), but the quality of the information produced by each trader increases. Overall, total information acquisition costs increase, but the quality of the information available to the insurer decreases. As a result, reinsurance dominates more strongly, the larger γ.

Summarizing, Figure 1 shows that when the fixed information acquisition cost k is large, reinsurance is preferred because the insurer would pay for this cost multiple times if he selected the financial market. For low γ, the financial market does produce better information than reinsurance, but it is subject to a Hirshleifer effect in the sense that the extra information produced is not worth its cost. When the degree of redundancy in the information is large, however, the financial market is unable to produce better quality information than the reinsurer in spite of its higher information acquisition costs—information production by the reinsurer is much more efficient because it avoids duplication.

The Impact of Information Acquisition Costs: What would it take for the financial market to dominate reinsurance? From the above discussion, one factor that could help is a lower fixed cost of information acquisition, k. Granted, a lower k would increase the number of informed traders, but it may decrease the product Nk. Figure 2 contrasts the solution of the model in the base case (left panels) with that for $k = 0.1m$ (right panels).[34] With low fixed costs k, for $\gamma \leq 0.75$, the number of informed traders in the financial market is much larger than in the base case at about 400, and the financial market dominates reinsurance. Two factors contribute to this effect. First, although total information acquisition costs are still higher for the financial market than for reinsurance, the financial market's information cost disadvantage is much smaller than in the base case at about $30m$. Second, because the larger number of traders provides for better quality information, the financial market's capital cost advantage is slightly higher than in the base case. Note that as in the base case, the financial market provides better information than reinsurance for $\gamma < 0.7$; however, the extra information is worth the extra cost because of the low k.

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[34]For each of the settings considered in the remainder of this section, all parameter values that are not mentioned explicitly are the same as in the base case. Other than those in the base case, not all the parameter values we use are realistic. We sometimes use extreme values because such values have the merit of delivering stark results, thereby clearly illustrating the comparative statics of the model.

The situation when $\gamma > 0.75$ is very different: informed traders acquire information beyond $1/\overline{v}$, the number of informed traders falls sharply, and the performance of the financial market deteriorates significantly. The reason is that although not very valuable because redundant, information beyond $1/\overline{v}$ is very costly to acquire: when k is much lower than c, it is cheaper to have numerous people buy imprecise information than have few people acquire precise information. However, when $\gamma > 0.75$, the financial market produces the second outcome, making its use to transfer risk prohibitively costly. Granted, the reinsurer acquires higher quality information than does an individual trader in the financial market, at a higher cost. However, that cost is incurred only once—reinsurance avoids the duplication in information production that plagues the financial market for large γ because of the large variable cost c.

Figure 2 considered the impact of low fixed costs k. Figure 3 contrasts the model's solution in the base case (left panels) with a situation with low variable costs $c = 0.12m$ (right panels). When variable costs are low, it is much more efficient for a single agent to acquire very precise information than for numerous agents to pay the fixed cost k and acquire relatively imprecise information. Reflecting this fact, reinsurance provides better information than the financial market for all γ, at a much lower cost. The better quality of the information provided by reinsurance strongly reduces the financial market's capital cost advantage compared to the base case. Thus, for low c and large k, reinsurance strongly dominates the financial market for all γ.

Further analysis, not reported in a figure for brevity, reveals that the ratio c/k constitutes a key determinant of the preferred form of risk transfer. For instance, when both c and k are 50 times smaller than in the base case (i.e., $c = 0.12m$ and $k = 0.1m$), the quality of the information provided by reinsurance exceeds that provided by the financial market except when γ is very small, and the total information acquisition cost is much higher for the financial market than for reinsurance. As a result, and as in the base case from Figure 1, reinsurance dominates the financial market for all γ.

The implication of Figures 2 and 3 is that two characteristics of information production favor the financial market over reinsurance: highly convex information production costs (in our context, variable costs c that exceed fixed costs k), and low redundancy in information production γ. The first makes it cost-efficient to divide information acquisition among many agents; the second ensures that duplication in information production is not a con-

cern. The importance of information redundancy and information acquisition costs for the choice between public and private financing has already been analyzed by Subrahmanyam and Titman (1999). What our analysis reveals is that in addition to the *level* of information acquisition costs, their *convexity* is critical for this decision. The consequence is that technological innovations in information production that affect fixed and variable information production costs differently impact the preferred form of risk transfer: innovations that reduce fixed costs favor the financial market, while innovations that reduce variable costs favor reinsurance.

Liquidity Trading: There is a widespread view that the presence of numerous hedgers and liquidity traders supports the use and development of financial markets.[35] In order to determine whether this is indeed the case, consider the effect of increasing the volatility of liquidity trader demand to $\sqrt{v_z} = 5m$, five times its initial value, while keeping all other parameters as in the base case. The results are reported in the left panels of Figure 4. The increased presence of liquidity traders stimulates both the number of informed traders in the financial market and the quality of the information that each trader acquires to such an extent that the quality of the information reflected in the price exceeds that provided by reinsurance regardless of the degree of information redundancy. Interestingly, for $\gamma > 0.45$, each trader even acquires more precise information than the reinsurer. Although the increased information acquisition in the financial market is favorable from a capital cost perspective, the cost of the information produced is prohibitively large at about $500m$ or more, illustrating the Hirshleifer effect in a very stark way. Thus, rather than making the financial market perform better, the presence of numerous hedgers and liquidity traders causes reinsurance to be preferred.

The preceding result suggests that it may be necessary to restrict rather than encourage liquidity trader participation in order for the financial market to dominate reinsurance. This is confirmed in the right panels of Figure 4, which show the model's solution when the volatility of liquidity trader demand is reduced to $\sqrt{v_z} = 0.1m$, one-tenth its initial value. The financial market now dominates for all γ. This finding is consistent with the success of catastrophe bonds noted in the Introduction. Such bonds have for the most part been sold under Rule 144A to Qualified Institutional Buyers (QIBs) and are traded in OTC markets:

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[35]See for example Cuny (1993).

there are few liquidity traders in OTC markets; few QIBs can be considered liquidity traders, in the sense of consistently sustaining trading losses to informed traders.[36]

What does it take for the financial market to dominate reinsurance when the variability of hedging demand is large? The preceding analysis suggests that a very low fixed cost k may achieve this result, and Figure 5, which contrasts the case $\sqrt{v_z} = 5m$ and $k = 5m$ considered previously (left panels) with the case $\sqrt{v_z} = 5m$ and $k = 0.001m$ (right panels), reveals that this is indeed the case. Observe that when fixed costs are very low, the financial market dominates reinsurance for $\gamma \leq 0.4$, i.e., for values of γ for which the number of traders is extremely large at about 25,000, but none of the traders acquires information beyond $1/\overline{v}$. As soon as individual traders begin acquiring information beyond $1/\overline{v}$, however, total information acquisition costs in the financial market become prohibitively large, and reinsurance is preferred. Thus, the picture that emerges from Figure 5 is that when liquidity trading demand is highly variable, the financial market dominates only if both the fixed cost of information acquisition and the degree of information redundancy are small—these are the same factors that were identified in Figures 2 and 3, but the required values become more extreme, the larger $\sqrt{v_z}$. We view the present case as representative—within the context of our model and for low γ—of successful financial exchanges.

Loss Uncertainty and Signal Precision: The preceding analysis reveals that low liquidity trading favors the financial market because it limits informed traders' ability to profit from the information they acquire, reducing the severity of the Hirshleifer effect. Intuitively, one could expect the same effect to arise if the prior uncertainty about the loss about which information can be acquired, $\sqrt{v_\delta}$, is small. The left panel of Figure 6, which shows the solution of the model when the uncertainty about the loss is reduced to $\sqrt{v_\delta} = 250$, one-sixth its value in the base case, confirms this intuition. Limited gain opportunities from trading attract fewer informed traders in the financial market, significantly reducing its information cost disadvantage compared to the base case. At the same time, reflecting the fact that when the uncertainty about the loss is small, there is little gain from reducing it, the reinsurer does not acquire information beyond $1/\overline{v}$. Although the insurer's payoff improves both for the financial market and for reinsurance compared to the base case, the financial market's performance improvement is stronger. Thus, paradoxically, phenomena that lead

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[36]Rule 144A dispenses from SEC registration requirements securities whose sale and trading are restricted to QIBs; QIBs are institutions that have at least $100m under management.

to an increase in loss uncertainty, such as global warming, may constitute an opportunity rather than a threat for reinsurance companies.

The dominance of financial markets for low loss uncertainty is consistent with Hagendorff, Hagendorff, and Keasey's (2010) finding that stock market reaction to catastrophe bond issuance is higher for issuers with less volatile loss ratios. It may provide a tentative explanation for the relative success of the catastrophe contracts traded on the Chicago Mercantile Exchange: recall from the Introduction that the contracts once trading on other exchanges since have been delisted. Whereas these other contracts were based on actual losses, the CME contracts are based on what are effectively expected losses.[37] As (conditional) expected losses are less volatile that actual losses, the relative success of the CME contracts may be attributable the lesser production of information by informed traders where loss uncertainty is lower.[38]

Note that the small initial uncertainty about the loss causes the payoff from using the financial market in the left panel of Figure 6 to be increasing in γ. The reason is that as γ increases, the decline in the number of traders produces savings in information acquisition costs that significantly exceed the modest increase in capital cost caused by the deterioration in information quality—when $\sqrt{v_\delta}$ is low, the insurer does not need to hold much capital anyway.

Figures 2 and 5 revealed that a low fixed cost of information acquisition k favors the financial market. Since k is the cost of obtaining information of precision $1/\overline{v}$, one could expect a lower $\overline{v}$ to favor the financial market as well. The right panels of Figure 6, which show the model's solution for $\sqrt{\overline{v}} = 250$, one-fourth its value in the base case, reveal that this is not the case. The intuition for this result is quite simple: when $\overline{v}$ is small, information acquisition by a single agent produces a relatively precise estimate of the value of the loss. It

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[37]The CME hurricane contracts are based on the CME Hurricane Index (CHI), which the CME describes as follows: 'Using publicly available data from the National Hurricane Center of the National Weather Service, the CHI calculates the *potential* for damage for each official storm by reference to its maximum wind velocity and size (radius).' (Emphasis added.) There is no reference to actual losses.

[38]To see that conditional expected losses are less volatile that actual losses, recall the relation

$$var\left[x\right] = E\left[var\left[x\left|y\right.\right]\right] + var\left[E\left[x\left|y\right.\right]\right]$$

and set $x = l + \delta$ and $y = i_{NWS}$ where i_{NWS} denotes publicly available National Weather Service data to conclude

$$var\left[E\left[l + \delta\left|i_{NWS}\right.\right]\right] = var\left[l + \delta\right] - E\left[var\left[l + \delta\left|i_{NWS}\right.\right]\right] < var\left[l + \delta\right].$$

is therefore not worth paying the cost k multiple times (the outcome in the financial market), and reinsurance dominates.

Fraction of Risk Transferred: Figure 7 reports the model solution when the fraction of risk transferred $\bar{\tau}$ is reduced to 0.2 (panel (a)) or increased to 0.8 (panel (b)). As one would expect, reducing the fraction of risk transferred lowers information acquisition both for the financial market and for reinsurance. The reduction in the information produced in the financial market occurs both through the number of traders and through the precision of the information that each trader acquires. The overall impact of the lower information acquisition is a reduction of the financial market's information cost disadvantage to about half of its value in the base case reported in Figure 1, with the consequence that reinsurance dominates much less clearly than in the base case. The opposite effects arise when $\bar{\tau} = 0.8$ (panel (b)): information production increases in both the financial market and reinsurance; both the number of traders and the precision of the information that each trader acquires increase; the financial market's information cost disadvantage widens significantly; and reinsurance dominates more strongly than in the base case.

Capital Costs: How does the insurer's capital cost a_i affect the preferred form of risk transfer? Obviously, an increase in a_i has no effect on the quality of the information produced by the financial market and by the reinsurer. However, a larger a_i makes economizing on costly capital more important and therefore favors the form of risk transfer that provides better quality information. This effect is apparent in Figure 8, which contrasts the model's solution for the base case (left panels) with that when $a_i = 0.2$ (right panels). Although information production and the financial market's information cost disadvantage are the same in both cases, the financial market's capital cost advantage differs. For $\gamma \leq 0.7$ ($\gamma > 0.7$), the financial market provides better (worse) information than reinsurance, and the capital cost advantage is larger (smaller) for large a_i than in the base case. Thus, in this example, although reinsurance still dominates for all γ, the financial market performs comparatively better than in the base case for $\gamma \leq 0.7$ and worse for $\gamma > 0.7$.

Durbin (2001) and Froot (2001) suggest that a prior catastrophe that depletes the capital of the reinsurance industry and increases the reinsurer's capital cost a_r tends to favor the financial market. Figure 9, which contrasts the model's solution for the base case (left panels)

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with that for $a_r = 0.2$ (right panels), reveals that this is indeed the case. A higher a_r causes the financial market to perform better for two reasons. The first, obvious one is that the financial market's capital cost advantage increases. The second reason is that in an attempt to keep the amount of capital under control, the reinsurer reacts to the increased capital cost by acquiring very precise information—in the right panel of Figure 9, the reinsurer spends about $30m$ on information acquisition, significantly reducing the financial market's information cost disadvantage.

A prior catastrophe also depletes the capital of primary insurers. Figure 10 contrasts the model's solution for the base case (left panels) with that where, following a catastrophe, both the insurer's and the reinsurer's capital cost increase significantly to $a_i = 0.24$ and $a_r = 0.2$ (right panels). Observe that although it still performs better than in the base case, the financial market does not do as well as in Figure 9. In particular, it does not dominate reinsurance for large γ. The reason is that, as was shown in Figure 8, a large a_i tends to favor the form of risk transfer that produces better quality information: the insurer benefits from the extremely precise information acquired by the reinsurer, which reduces reinsurance's capital cost disadvantage.

Finally, observe that an increase in the stringency of capital requirements λ has the same impact as a proportionate increase in both a_i and a_r. For example, increasing λ from its base case value of 2.5 to 10 while leaving a_i and a_r at their base case values of 0.06 and 0.05, respectively, has exactly the same effect as leaving $\lambda = 2.5$ and setting $a_i = 0.24$ and $a_r = 0.20$, the situation considered in Figure 10. The fact that the financial market performs much better than in the base case for low γ and only slightly better for large γ can be understood as follows. More stringent capital requirements have no effect on information production in the financial market, but stimulate information acquisition by the reinsurer. This reduces the financial market's information cost disadvantage for all γ. At the same time, a higher λ increases capital costs both for the financial market and for reinsurance. For each form of risk transfer, the increase is smaller, the better the quality of the information provided. For reinsurance, where the quality of information is independent of γ, this translates into a constant increase in the capital cost. For the financial market, where the quality of the information is decreasing in γ, the increase in the capital cost is more pronounced, the larger γ. For instance, in the example considered in Figure 10, reinsurance's capital cost increases to about $350m$, compared to $120m$ in the base case. For the financial

market, the capital cost increases from about $40m$ to $190m$ for $\gamma = 0$, and from about $70m$ to about $250m$ for $\gamma = 1$—about 20% more. The consequence is that the financial market's capital cost advantage increases more strongly for low γ.

Summarizing, the numerical analysis in this section shows that large fixed information acquisition costs k, large redundancy in the information produced γ, large volatility of liquidity trading $\sqrt{v_z}$, large prior uncertainty about the loss $\sqrt{v_\delta}$, and a large fraction of risk transferred $\overline{\tau}$ tend to favor reinsurance. In contrast, a large variable cost of information acquisition c, large noise in the information acquired $\sqrt{v}$, and a large reinsurer cost of capital a_r tend to favor the financial market. An increase in the insurer's cost of capital a_i favors the form of risk transfer that produces the most precise information. More stringent capital requirements λ have the same effect as a proportionate increase in a_i and a_r; they tend to favor the financial market. Finally, large redundancy in the information produced, γ, favors reinsurance where loss uncertainty is high and financial markets where it is low. To the extent the base case parameters are representative of current conditions in the markets for natural catastrophe insurance, our model may be viewed as providing a unified if partial explanation for the success of OTC-traded catastrophe bonds and the relative failure of exchange-traded catastrophe futures and options.

5.2 The Insurer Can Acquire Information

We now turn to the case of a large insurer that also produces information and investigate how the insurer's variable information production cost c_i affects the preferred form of risk transfer. The solution methodology is similar to that in Section 5.1 with one addition, namely the determination of the insurer's optimal information acquisition strategy accounting for the response of the reinsurer and traders in the financial market (note that the insurer's optimal information acquisition strategy in both cases will typically differ).

The insurer's information production implies that for any parameter constellation, traders in the financial market and the reinsurer face lower uncertainty about δ than in Section 5.1, i.e. $v_{\delta|i} < v_\delta$. Thus, based on the results for a low v_δ in the left panel of Figure 6, one would expect the financial market to perform relatively better than in Section 5.1; furthermore, in those cases where the insurer chooses to acquire very precise information (yielding a low $v_{\delta|i}$, which will typically occur for low c_i), the financial market should perform better for large γ.

Figure 11, which reports the model's solution when the insurer's variable information production cost is high ($c_i = 20m$, left panels), and when it is low ($c_i = 1m$, right panels), confirms this intuition.[39],[40] In addition to informed traders' and the reinsurer's information acquisition policies, we also report the insurer's information acquisition policy in the financial market and reinsurance solutions (the curves are labeled "Insurer, FM" and "Insurer, Re" in the second panels from the top). When the insurer's information production cost is high, reinsurance dominates the financial market as it did in the base case without information production by the insurer considered in Figure 1, but the difference in the insurer's payoff between both forms of risk transfer is lower than in Figure 1. The reason that reinsurance still dominates the financial market is that although the insurer can use his own information production to deter entry and information production in the financial market, doing so is extremely costly. By contrast, when the insurer has low information production costs (right panels), he produces at moderate cost very precise information to deter entry and information production by traders in the financial market. This reduces the financial market's information cost disadvantage below its capital cost advantage, and the financial market is selected as the preferred form of risk transfer. As expected, greater information redundancy favors the financial market when the insurer's information acquisition cost is low: by making informed traders' information more similar, greater information redundancy further decreases these traders' opportunities to profit from trading, thereby further decreasing their entry into the financial market.

Analyzing the different parameter constellations considered in Section 5.1 but accounting for information production by the insurer reveals that most of the results established previously still hold. In particular, lower fixed costs k favor the financial market (more strongly so when c_i is high because the insurer has more difficulty preventing entry in that case), lower variable costs c favor reinsurance, high liquidity trading variability $\sqrt{v_z}$ favors reinsurance (again more strongly when c_i is high, for the same reason), low loss uncertainty v_δ favors the financial market (again more strongly when c_i is high, for the same reason), and high reinsurer cost of capital a_r favors the financial market. The two differences compared to

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[39]Note that although the two values we use for c_i happen to be higher and lower than those for traders in the financial market and the reinsurer in the base case ($c = 6m$), what drives the dominance of the financial market or reinsurance is the level of the insurer's information acquisition costs, not how they compare to traders' or the reinsurer's.

[40]The values of the parameters for the reinsurer and the financial market are the same as in the base case from Section 5.1. We also set $k_i = 5m$ for consistency; however, this parameter does not affect the preferred form of risk transfer.

the case without information acquisition by the insurer are that (1) a high minimum signal precision (i.e. low $\overline{v}$) favors the financial market because it causes $v_{\delta|i}$ to be very low (and therefore has the same effect as a low v_δ, in contrast to the results in Section 5.1), and (2) a high insurer cost of capital a_i favors the financial market for all γ because the insurer's loss uncertainty is lower with the financial market for all γ. In all these cases, when the insurer's information acquisition cost c_i is low, the financial market performs better for large γ, in line with the findings in Figure 11.

The results in Figure 4 showed that when the insurer cannot produce information, the presence of numerous hedgers and liquidity traders causes excessive information production by informed traders in the financial market, and reinsurance is preferred. As shown there, limiting the number of liquidity traders enhances the financial market's performance. The results in Figure 11 suggest that information production by the insurer may achieve the same goal. Figure 12, which reports the solution of the model when the variability of liquidity trading is high ($\sqrt{v_z} = 5m$) and the insurer can also produce information, confirms this intuition. When the insurer's information production cost is high ($c_i = 20m$, left panels), the financial market performs significantly worse than reinsurance as it did in the left panels of Figure 4. When the insurer's information cost is low ($c_i = 1m$, right panels), the financial market's performance improves significantly. Further analysis, not reported in a figure for brevity, reveals that when the insurer's information acquisition cost is even lower at $c_i = 0.1m$, the financial market dominates reinsurance for all γ. The implication of this result is that financial markets are a viable solution to transfer risk not only if liquidity trading can be limited, but also if insurers are able themselves to produce high quality information.

6   Conclusion

We investigate the suitability of securitization as an alternative to reinsurance for the purpose of transferring natural catastrophe risk. We characterize the conditions under which one or the other form of risk transfer dominates. We consider the case of an insurer who seeks to supplement the costly information it has produced about possible losses with information obtained from a reinsurer or prices in financial markets. Such information is valuable to the insurer, for it decreases that insurer's costly capital requirements: the better the insurer

understands the risk to which it is exposed, the lesser the amount of capital the insurer needs to guard against such risk. We find that informed traders who seek to benefit from trading in financial markets may in some cases produce more information than warranted by the primary objective of decreasing insurer capital requirements; there is 'too much' information. This is an instance of the 'Hirshleifer Effect' (Hirshleifer, 1971). The production of too much information at too high a cost in financial markets is more likely i) where the fixed costs of producing information are high, ii) where the variable costs of producing information are low, iii) where there are many liquidity traders, and iv) where losses are highly uncertain. Redundancy in the information produced—how similar are the pieces of information produced by informed traders in the financial markets—favors reinsurance where there is large loss uncertainty and securitization where there is little. To the extent our base case parameters are representative of current conditions in the markets for natural catastrophe insurance, our model may be viewed as providing a unified if partial explanation for the success of OTC-traded catastrophe bonds and the relative failure of exchange-traded catastrophe futures and options referred to in the Introduction.

Our study could be extended along several dimensions. First, one could allow the insurer simultaneously to reinsure and securitize. Second, one could explicitly account for the adverse selection and moral hazard issues that exist in the reinsurance industry. Third, one could construct a dynamic version of the model incorporating learning, thereby reflecting investors' growing familiarity with securitized catastrophe instruments. Finally, one could investigate whether there are differences in the degree of information redundancy across various types of natural catastrophes—earthquakes, floods, hurricanes, windstorms—in order to assess whether some of these risks are more amenable to being securitized than are others.

The insights from our analysis tentatively may extend beyond the transfer of natural catastrophe risk. Consider for example the transfer of credit risk through credit default swaps (CDSs). In the wake of the financial crisis, there has been much talk of requiring these to be traded on exchanges, in contrast to the OTC markets in which CDS trading hitherto has been concentrated. Our analysis suggests that the prospects for CDS exchange trading at least partially depend on the nature and costs of information about credit risk, the extent of liquidity trading in credit instruments, and the uncertainty of credit losses.

Appendix

A   Determination of Optimal Demand x_n

Recall from (5) that trader n chooses his optimal demand x_n by solving

$$\max_{x_n} E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1\\m\neq n}}^{N}\kappa i_m + z\right)\right]\Big|i_n\right] \tag{28}$$

Substituting $i_m = \delta + \sqrt{v}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_m\right)$ and using the fact that z and ϵ_m are independent of i_n, this expression can be rewritten as

$$\max_{x_n} x_n\left[\overline{\tau}E\left[\delta|i_n\right] - \zeta\left(x_n + (N-1)\kappa E\left[\delta|i_n\right] + (N-1)\kappa\sqrt{v}\gamma E\left[\xi|i_n\right]\right)\right]$$

$$= \max_{x_n} x_n\left[(\overline{\tau} - \zeta(N-1)\kappa)\frac{v_\delta}{v_\delta + v_n}i_n - \zeta x_n - \zeta(N-1)\kappa\gamma^2\frac{\sqrt{v_n}\sqrt{v}}{v_\delta + v_n}i_n\right] \tag{29}$$

Differentiating with respect to x_n and solving yields

$$x_n = \frac{1}{2\zeta}\frac{\overline{\tau}v_\delta - \zeta(N-1)\kappa\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)}{v_\delta + v_n}i_n \tag{30}$$

which is optimal demand (6) in the text.

B   Determination of the Optimal Information Acquisition Policy v_n

Recall from (8) that trader n chooses his optimal information acquisition policy v_n by solving

$$\max_{v_n} E\left[E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1\\m\neq n}}^{N}\kappa i_m + z\right)\right]\Big|i_n\right]\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{31}$$

Substituting $i_m = \delta + \sqrt{v}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_m\right)$ and using the fact that z and ϵ_m are independent of i_n, this expression can be rewritten as

$$\max_{v_n} \quad E\left[x_n\left[(\overline{\tau} - \zeta(N-1)\kappa)\frac{v_\delta}{v_\delta + v_n}i_n - \zeta x_n - \zeta(N-1)\kappa\gamma^2\frac{\sqrt{v_n}\sqrt{v}}{v_\delta + v_n}i_n\right]\right]$$
$$-c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{32}$$

From (30), we have

$$\frac{\overline{\tau}v_\delta - \zeta\left(N-1\right)\kappa\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)}{v_\delta + v_n}i_n = 2\zeta x_n \tag{33}$$

Hence, problem (32) becomes

$$\max_{v_n} E\left[x_n\left[2\zeta x_n - \zeta x_n\right]\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k$$
$$= \max_{v_n} E\left[\zeta x_n^2\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{34}$$

Substituting x_n from (30) and using the fact that $E[i_n^2] = v_\delta + v_n$ then yields

$$\max_{v_n} \frac{1}{4\zeta}\frac{\left(\overline{\tau}v_\delta - \zeta\kappa\left(N-1\right)\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)\right)^2}{v_\delta + v_n} - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{35}$$

Note that the first term is decreasing in v_n, indicating that there is a benefit to improving the quality of the information.

Differentiating with respect to v_n, the first-order condition corresponding to an interior solution reads

$$\frac{1}{4\zeta}\frac{\overline{\tau}v_\delta - \zeta\kappa(N-1)\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)}{(v_\delta + v_n)^2} \times$$
$$\left(\zeta\kappa(N-1)\gamma^2\frac{\sqrt{v}}{\sqrt{v_n}}(v_\delta + v_n) + \left(\overline{\tau}v_\delta - \zeta\kappa\left(N-1\right)\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)\right)\right) = c\frac{\overline{v}}{v_n^2} \tag{36}$$

Imposing the symmetry conditions $\kappa_n = \kappa$ and $v_n = v$, we have

$$\kappa = \frac{\overline{\tau}v_\delta}{\zeta\left[(N+1)v_\delta + \left(2 + (N-1)\gamma^2\right)v\right]} \tag{37}$$

Since $P = \bar{\tau}\bar{l} + \zeta Q = \bar{\tau}\bar{l} + E[\bar{\tau}\delta | Q]$, ζ is the coefficient in the regression of $\bar{\tau}\delta$ on Q, i.e.,

$$\zeta = \frac{\text{cov}(\bar{\tau}\delta, Q)}{\text{var}(Q)} = \frac{\bar{\tau} v_\delta \sqrt{N(v_\delta + v)}}{\sqrt{v_z}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]} \tag{38}$$

Inserting this expression into (37) then yields

$$\kappa = \sqrt{\frac{v_z}{N(v_\delta + v)}} \tag{39}$$

Setting $v_n = v$ for a symmetric equilibrium and substituting κ and ζ from (37) and (38), the first order condition (36) becomes

$$\frac{\bar{\tau}(2 + (N-1)\gamma^2)\sqrt{v_z}v_\delta}{2\sqrt{N}\sqrt{v_\delta + v}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]} = c\frac{\bar{v}}{v^2} \tag{40}$$

which is (11) in the text.

C   Determination of Expected Profit Π_f

From (34), given $v_n = v$, the trader's expected profit is given by

$$\Pi_f = E[\zeta x_n^2] - c\left(\frac{\bar{v}}{v} - 1\right) - k \tag{41}$$

Using (9) and (10), the first term can be rewritten as

$$
\begin{aligned}
E[\zeta x_n^2] &= \zeta \kappa^2 (v_\delta + v) \\
&= \left(\frac{\bar{\tau} v_\delta \sqrt{N(v_\delta + v)}}{\sqrt{v_z}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]}\right)\left(\frac{v_z}{N(v_\delta + v)}\right)(v_\delta + v) \\
&= \frac{\bar{\tau}\sqrt{v_z}v_\delta\sqrt{v_\delta + v}}{\sqrt{N}\left[(N+1)v_\delta + (2 + (N-1)\gamma^2)v\right]}
\end{aligned} \tag{42}
$$

Inserting this expression into (41) yields (12).

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Figure 1: The preferred form of risk transfer in the base case.

This figure shows the solution of the model as a function of the degree of information redundancy γ for the base case parameter values $\bar{l} = -500m$, $\sqrt{v_l} = 500m$, $\sqrt{v_\delta} = 1,500m$, $\sqrt{\bar{v}} = 1,000m$, $\sqrt{v_z} = 1m$, $\lambda = 2.5$, $\bar{\tau} = 0.5$, $a_i = 0.06$, $a_r = 0.05$, $k = 5m$, and $c = 6m$. The first panel shows the number of informed traders in the financial market, N. The second panel reports the (inverse) quality of the information acquired by the individual traders in the financial market, $\sqrt{v}$, and by the reinsurer, $\sqrt{v_r}$. The third panel reports the loss uncertainty facing the insurer once information has been acquired, $SD\left[l + \delta \,|Q\right]$ for the financial market and $SD\left[l + \delta \,|i_r\right]$ for reinsurance. The fourth panel reports the total information acquisition cost, $N\left(c\left(\bar{v}/v - 1\right) + k\right)$ for the financial market and $c\left(\bar{v}/v_r - 1\right) + k$ for reinsurance. The fifth panel reports the total capital cost, $\lambda a_i \left(1 - \bar{\tau}\right) SD[l+\delta|Q]$ for the financial market and $\lambda\left[a_i \left(1 - \bar{\tau}\right) + a_r\bar{\tau}\right] SD[l+\delta|i_r]$ for reinsurance. The sixth panel shows the payoffs to the insurer from using the financial market and reinsurance, $\Gamma_{i,f}$ and $\Gamma_{i,r}$.

Figure 2: Low fixed information acquisition costs k favor the financial market.

Panel a shows the solution of the model for the base case from Figure 1 in which $k = 5m$. Panel b considers the solution when fixed costs are reduced to $k = 0.1m$.
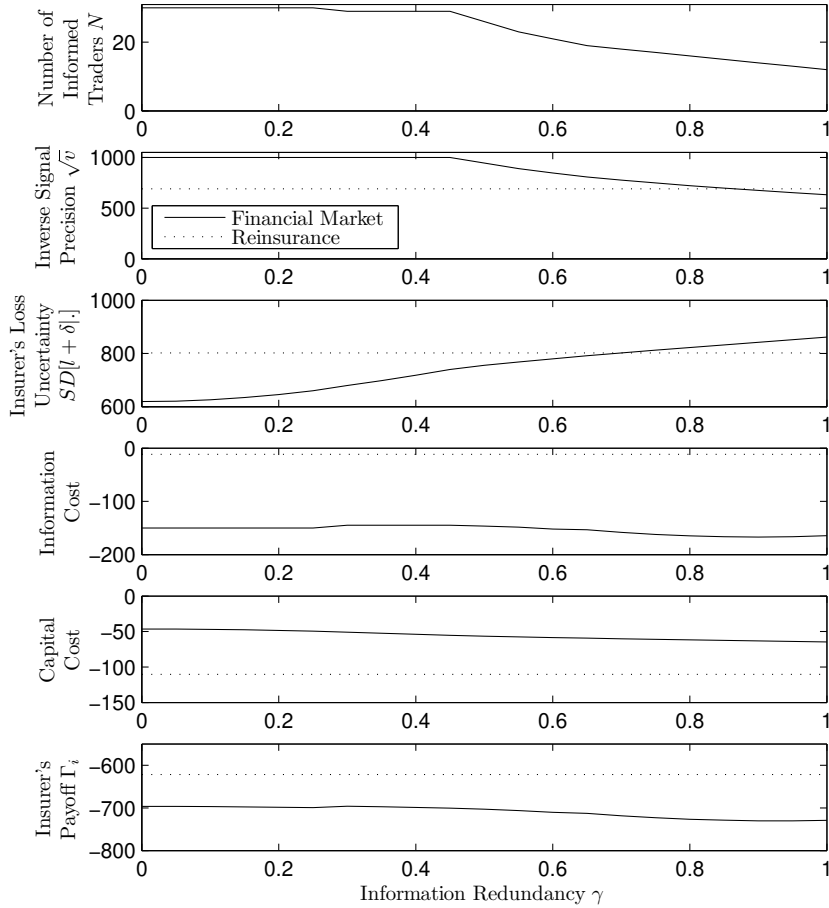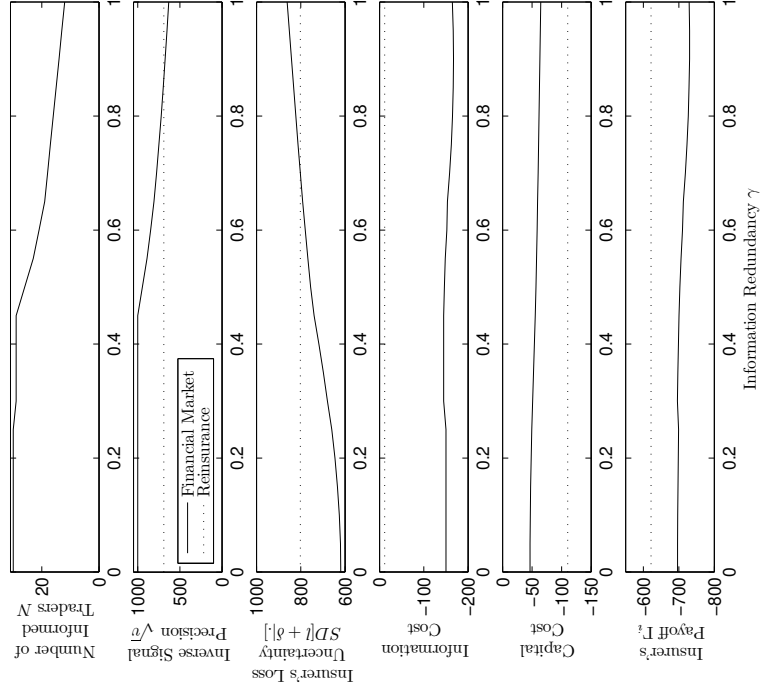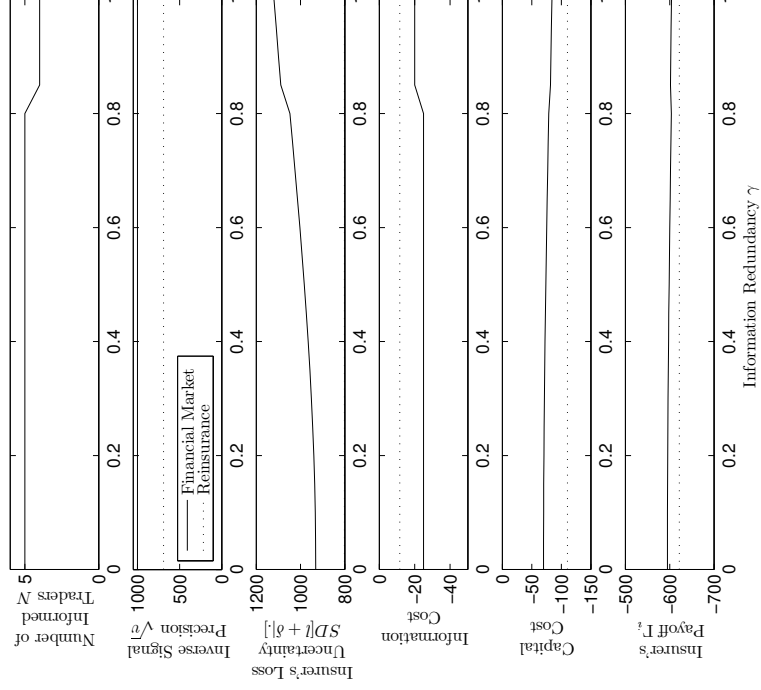

(a) Base Case ($k = 5m$).
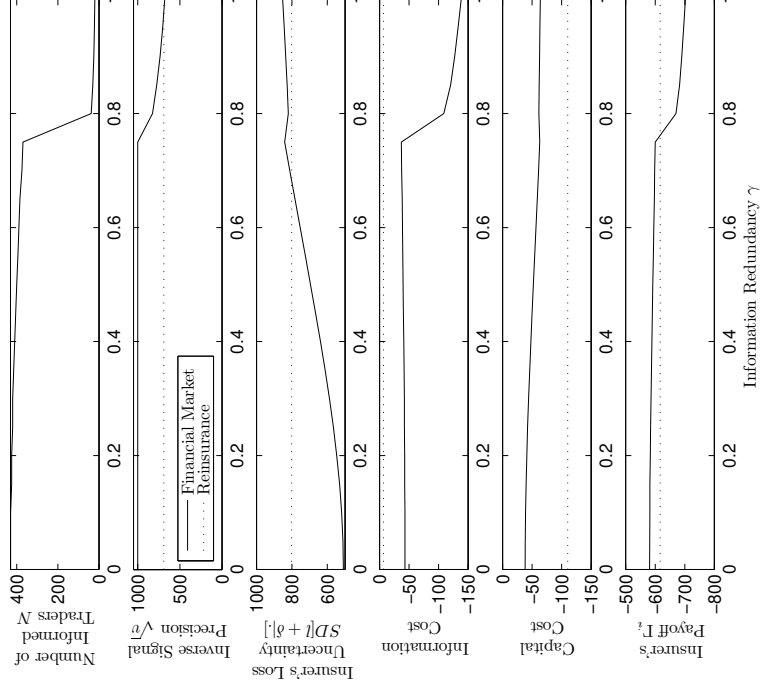
(b) Low fixed costs $k = 0.1m$.

Figure 3: Low variable information acquisition costs c favor reinsurance.

Panel a shows the solution of the model for the base case from Figure 1 in which $c = 6m$. Panel b considers the solution when variable information acquisition costs are reduced to $c = 0.12m$.
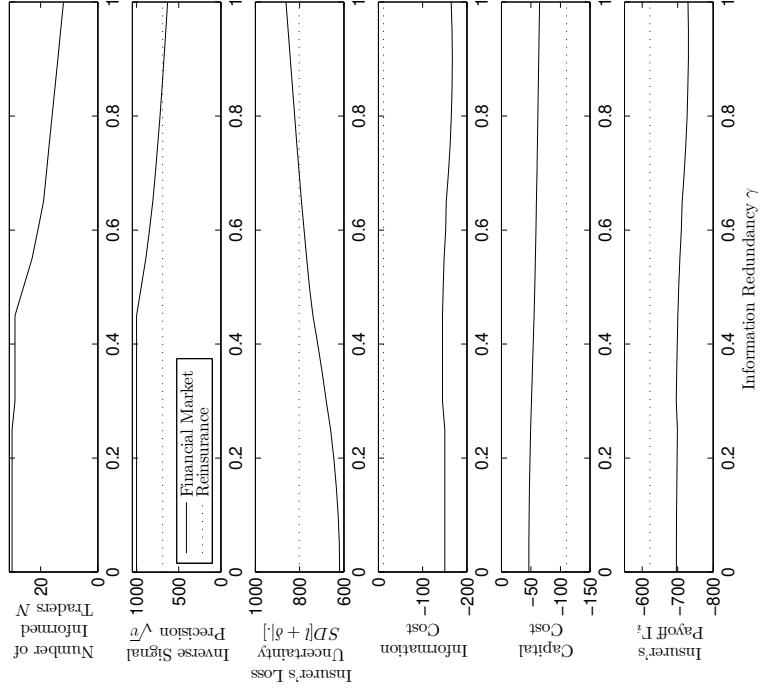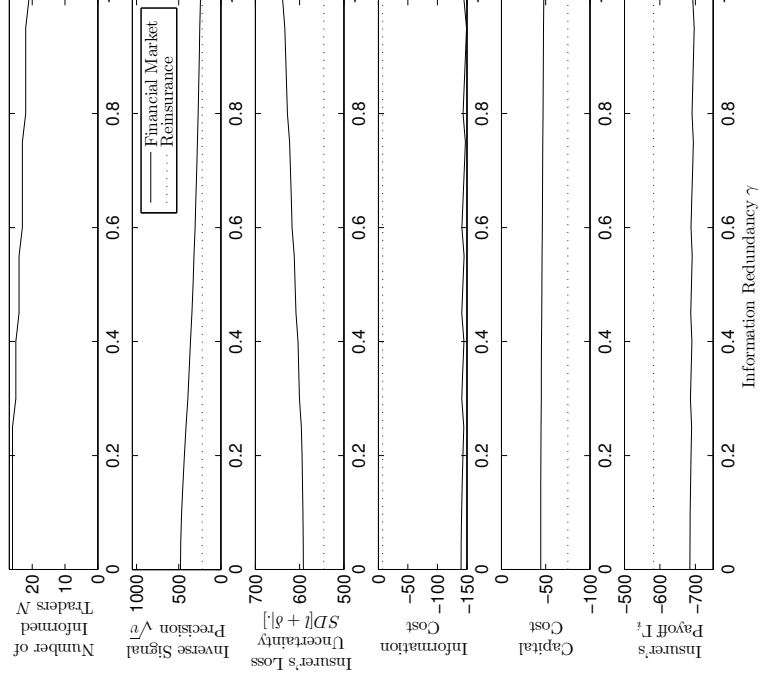
(a) Base Case ($c = 6m$).

(b) Low variable costs $c = 0.12m$.

Figure 4: Liquidity trading adversely affects the financial market's performance.

Panel a shows the solution of the model for high variability of liquidity trader demand $\sqrt{v_z} = 5m$. Panel b considers a situation with low variability of liquidity trader demand $\sqrt{v_z} = 0.1m$.
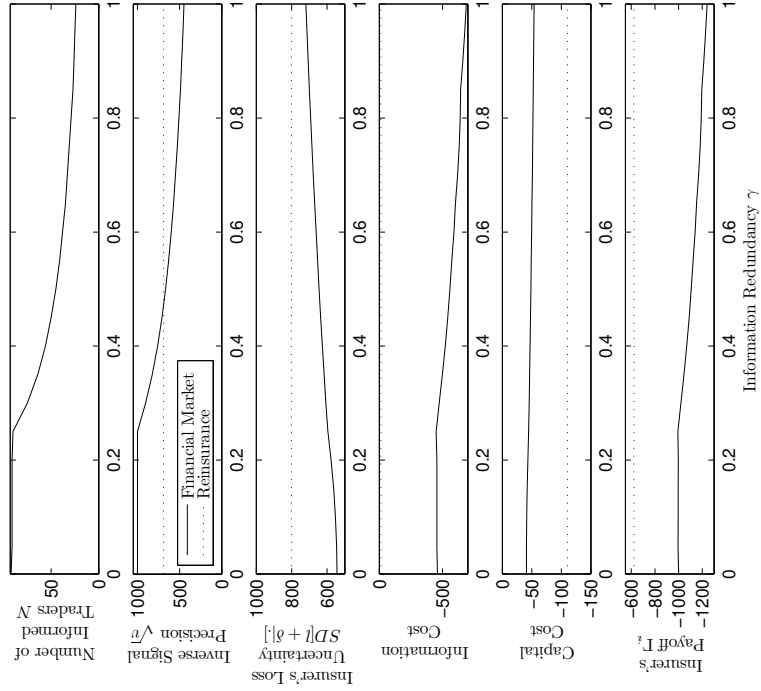
(a) High liquidity trading $\sqrt{v_z} = 5m$.

(b) Low liquidity trading $\sqrt{v_z} = 0.1m$.

Figure 5: Low fixed costs mitigate the adverse impact of high liquidity trading on the financial market.

Panel a shows the solution of the model for high variability of liquidity trader demand $\sqrt{v_z} = 5m$ and the fixed costs from the base case, $k = 5m$. Panel b considers a situation with low fixed costs, $k = 0.001m$.
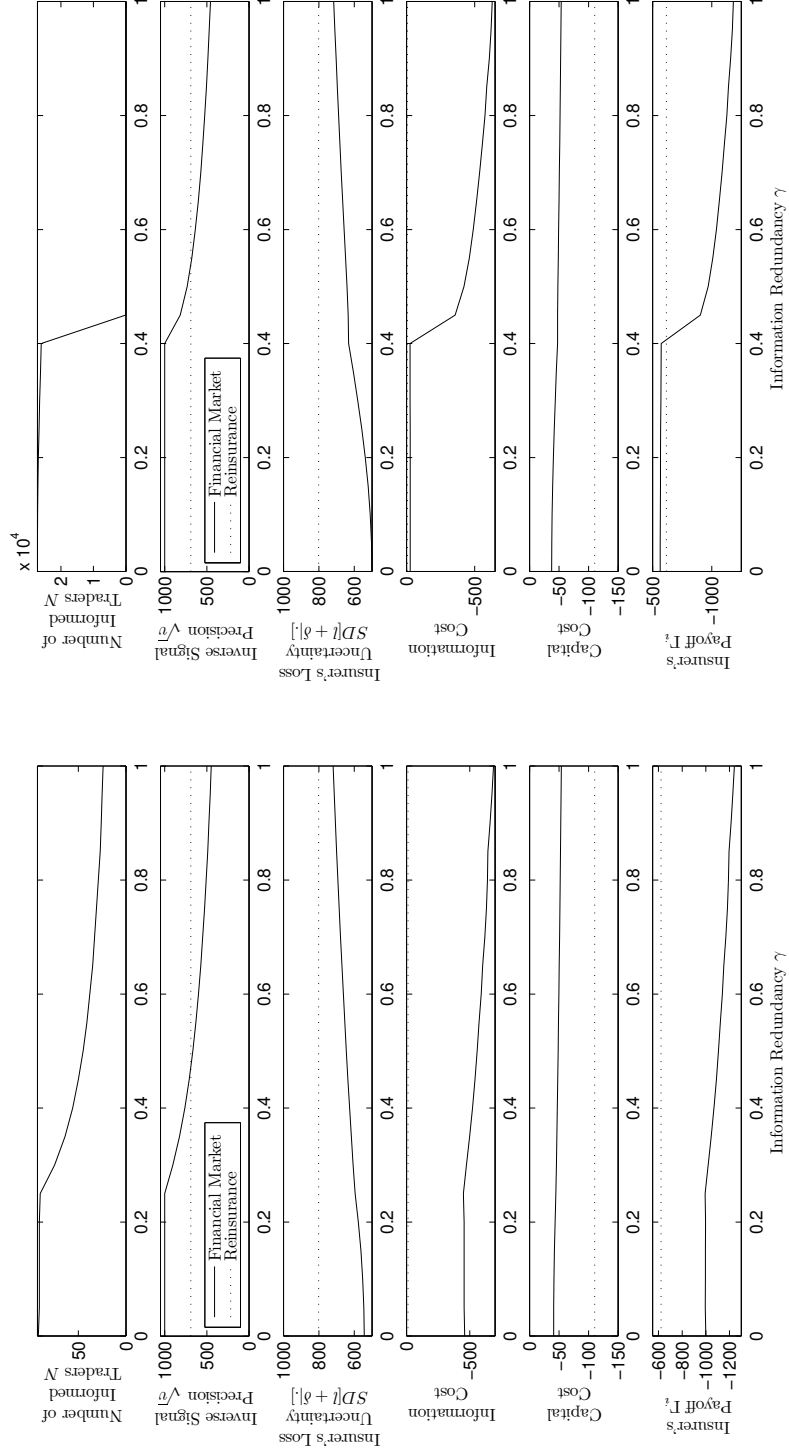
(a) High liquidity trading $\sqrt{v_z} = 5m$, high fixed costs $k = 5m$.   (b) High liquidity trading $\sqrt{v_z} = 5m$, low fixed costs $k = 0.001m$.

Figure 6: Low loss uncertainty favors the financial market, but high minimum signal precision favors reinsurance.

Panel a shows the solution of the model for low loss uncertainty $\sqrt{v_\delta} = 250$, one-sixth the value in the base case of Figure 1. Panel b considers a situation where the minimum signal precision exceeds that in the base case, $\sqrt{\bar{v}} = 250$.
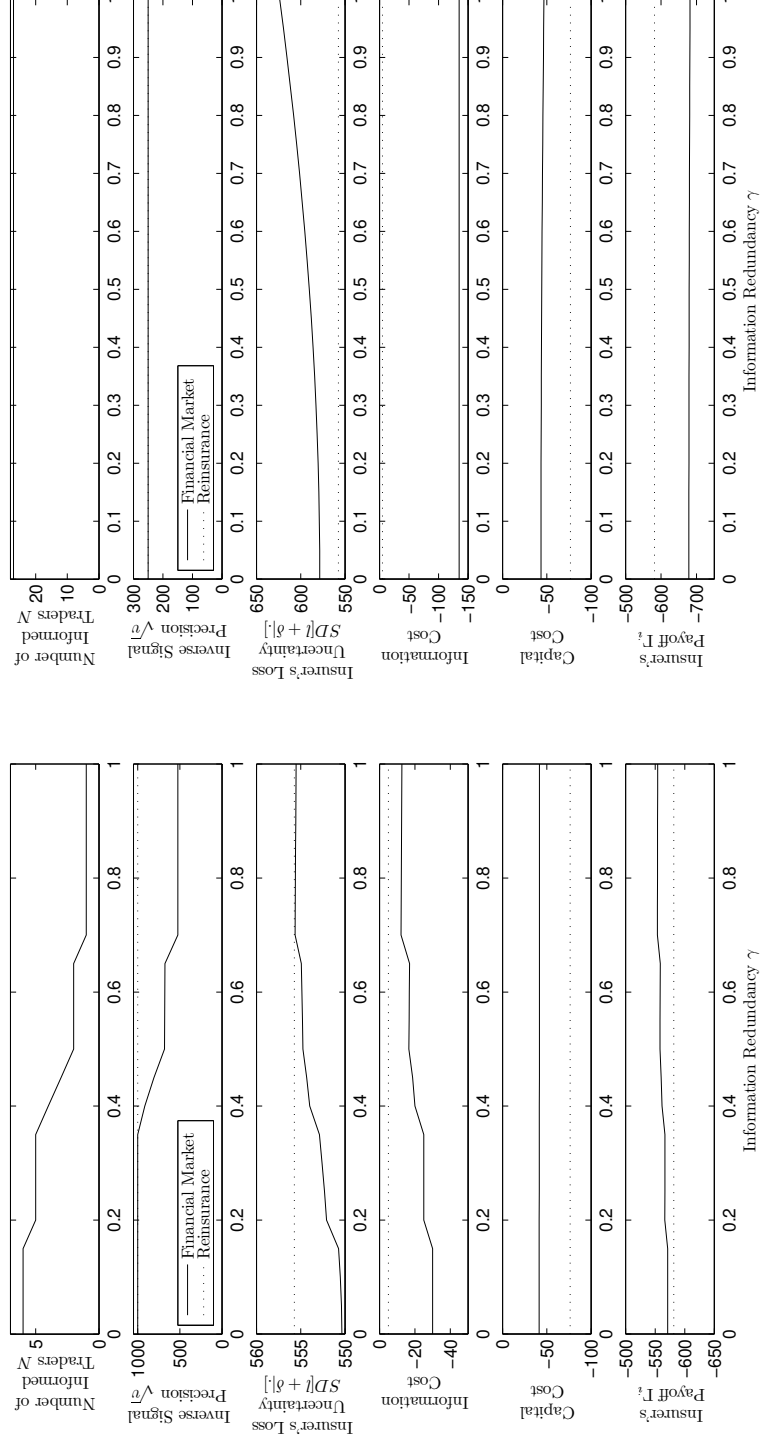
(a) Low loss uncertainty $\sqrt{v_\delta} = 250$.

(b) High minimum signal precision $\sqrt{\bar{v}} = 250$.

Figure 7: A higher fraction of risk transferred favors reinsurance.

Panel a shows the solution of the model when the fraction of risk transferred is reduced to $\bar{\tau} = 0.2$, versus $\bar{\tau} = 0.5$ in the base case of Figure 1. Panel b considers a situation where the fraction of risk transferred is increased to $\bar{\tau} = 0.8$.
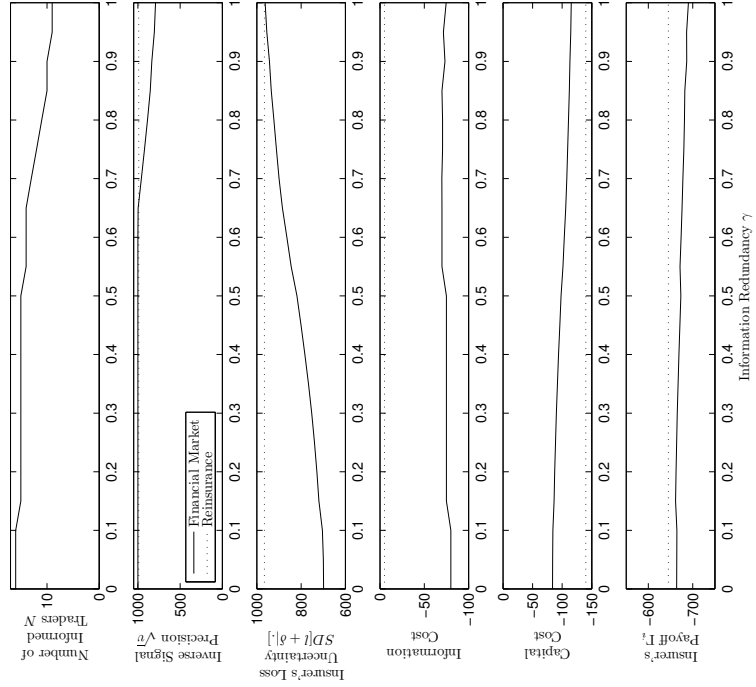

(a) Low fraction of risk transferred ($\bar{\tau} = 0.2$).
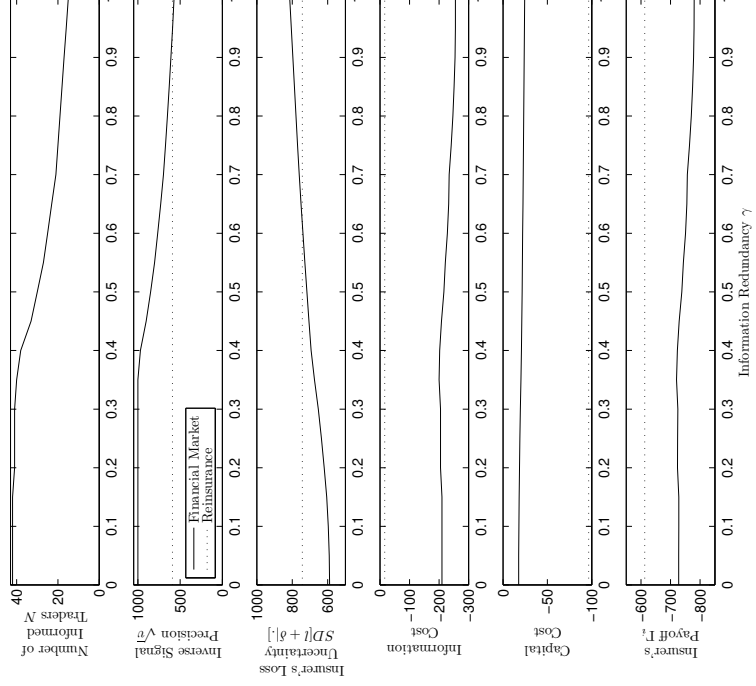
(b) High fraction of risk transferred ($\bar{\tau} = 0.8$).

Figure 8: High insurer cost of capital favors the form of risk transfer for which the insurer's loss uncertainty is lower.

Panel a shows the solution of the model for the base case in Figure 1 in which $a_i = 0.06$. Panel b considers a situation where the insurer's cost of capital is much larger at $a_i = 0.2$.
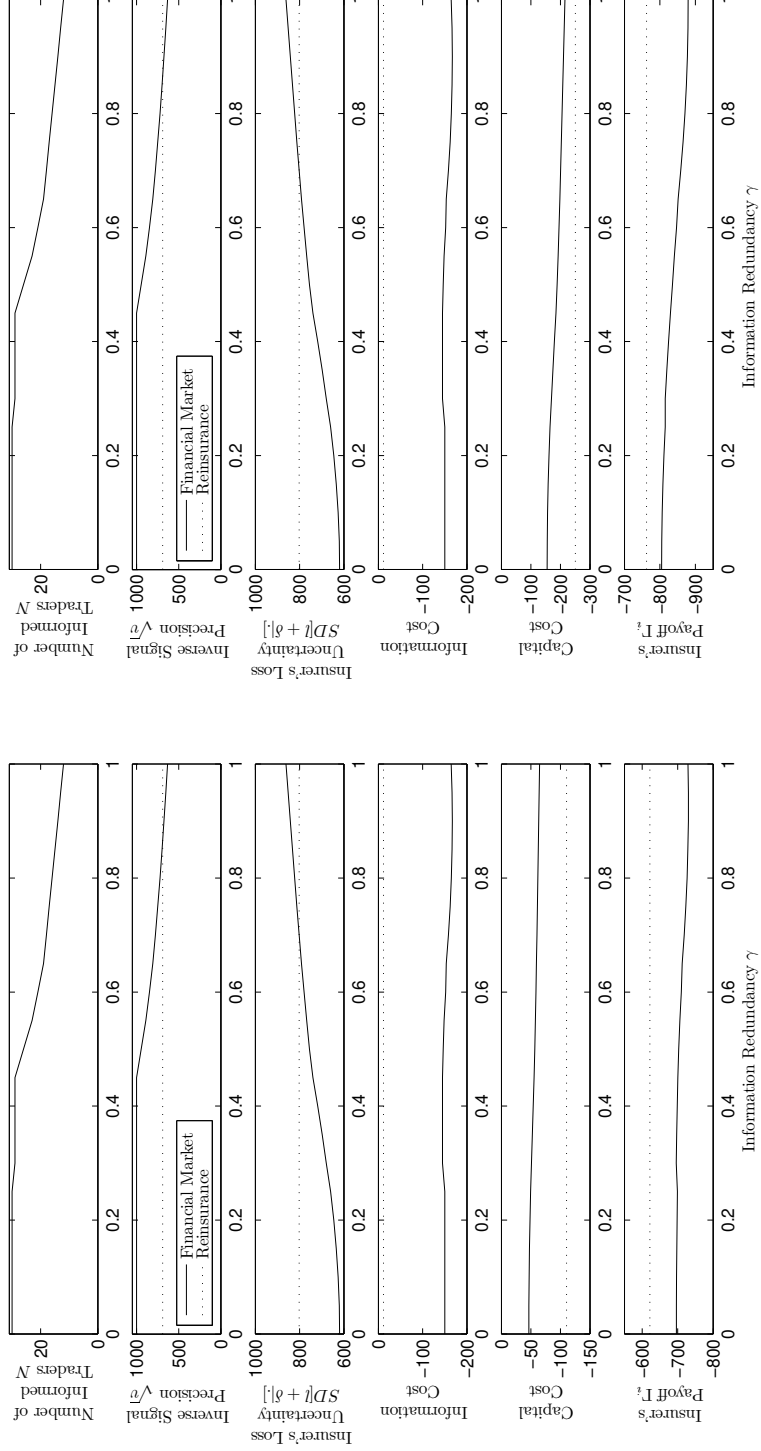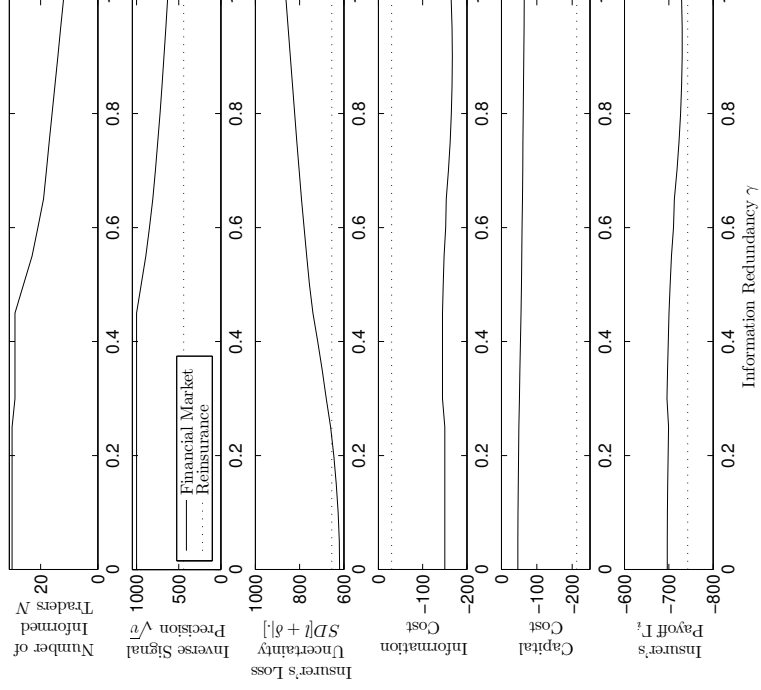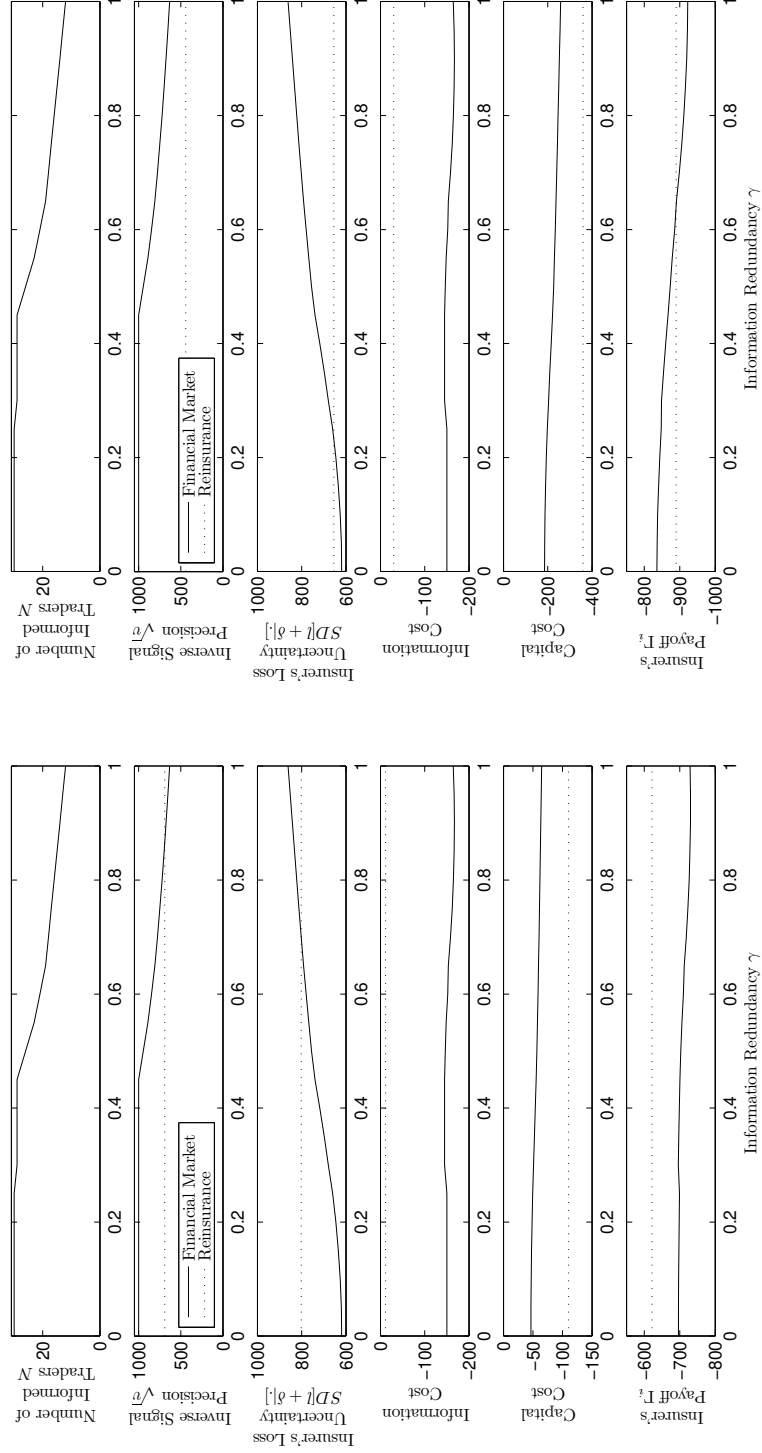

(a) Base case ($a_i = 0.06$).

(b) High insurer cost of capital ($a_i = 0.2$).

Figure 9: High reinsurer cost of capital favors the financial market.

Panel a shows the solution of the model for the base case in Figure 1 in which $a_r = 0.05$. Panel b considers a situation where the reinsurer's cost of capital is much larger at $a_r = 0.2$.
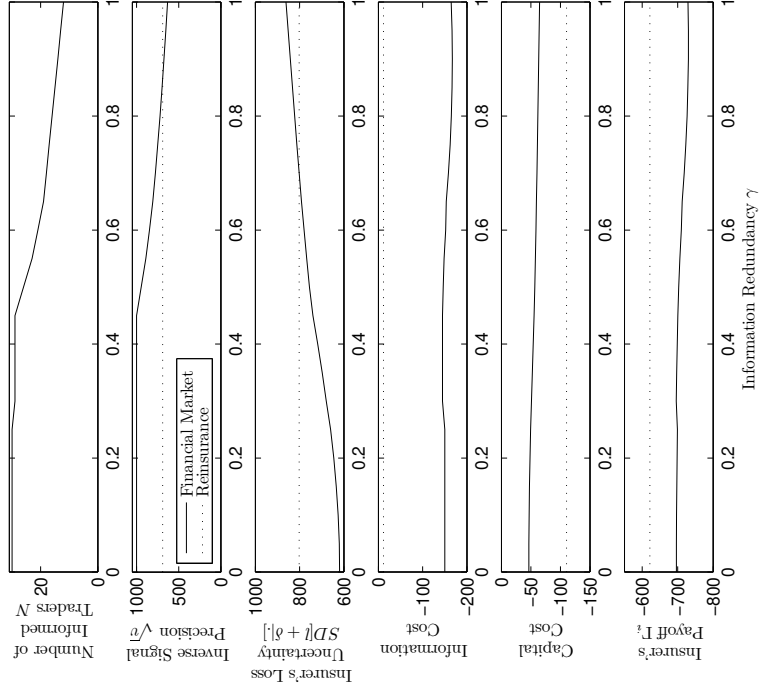
(a) Base case ($a_r = 0.05$).

(b) High reinsurer cost of capital ($a_r = 0.2$).

Figure 10: High costs of capital for both the insurer and the reinsurer favor the financial market.

Panel a shows the solution of the model for the base case in Figure 1 in which $a_i = 0.06$ and $a_r = 0.05$. Panel b considers a situation where both the insurer's and the reinsurer's cost of capital are much larger at $a_i = 0.24$ and $a_r = 0.2$, respectively.

(a) Base case ($a_i = 0.06$, $a_r = 0.05$).

(b) High cost of capital for both insurer and reinsurer ($a_i = 0.24$, $a_r = 0.2$).

Figure 11: Information production by the insurer can deter excessive information production by the financial market and cause the financial market to become the preferred form of risk transfer.

Panel a shows the solution of the model when the insurer is also able to acquire information and its variable information acquisition cost is high, $c_i = 20m$. Panel b considers a situation where the insurer's variable information acquisition cost is low, $c_i = 1m$.
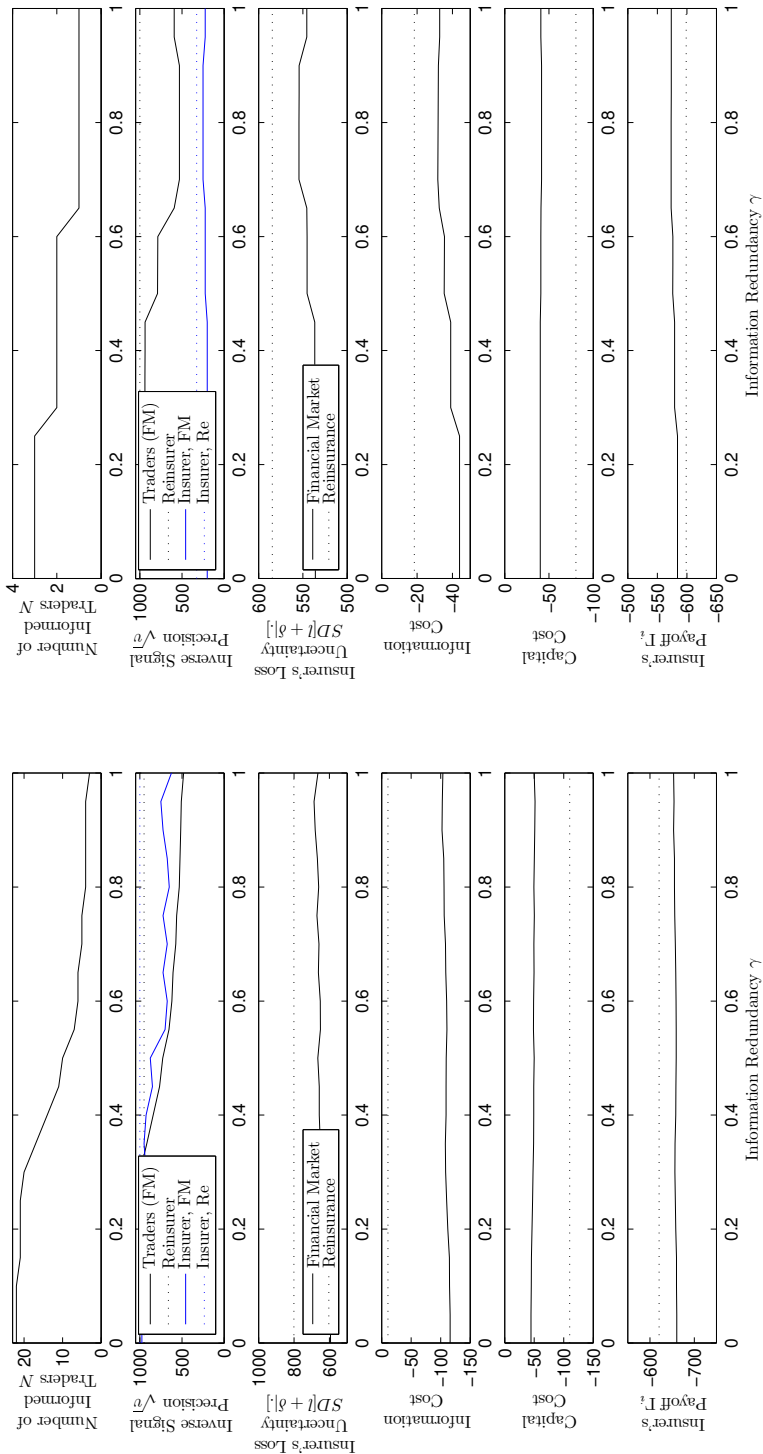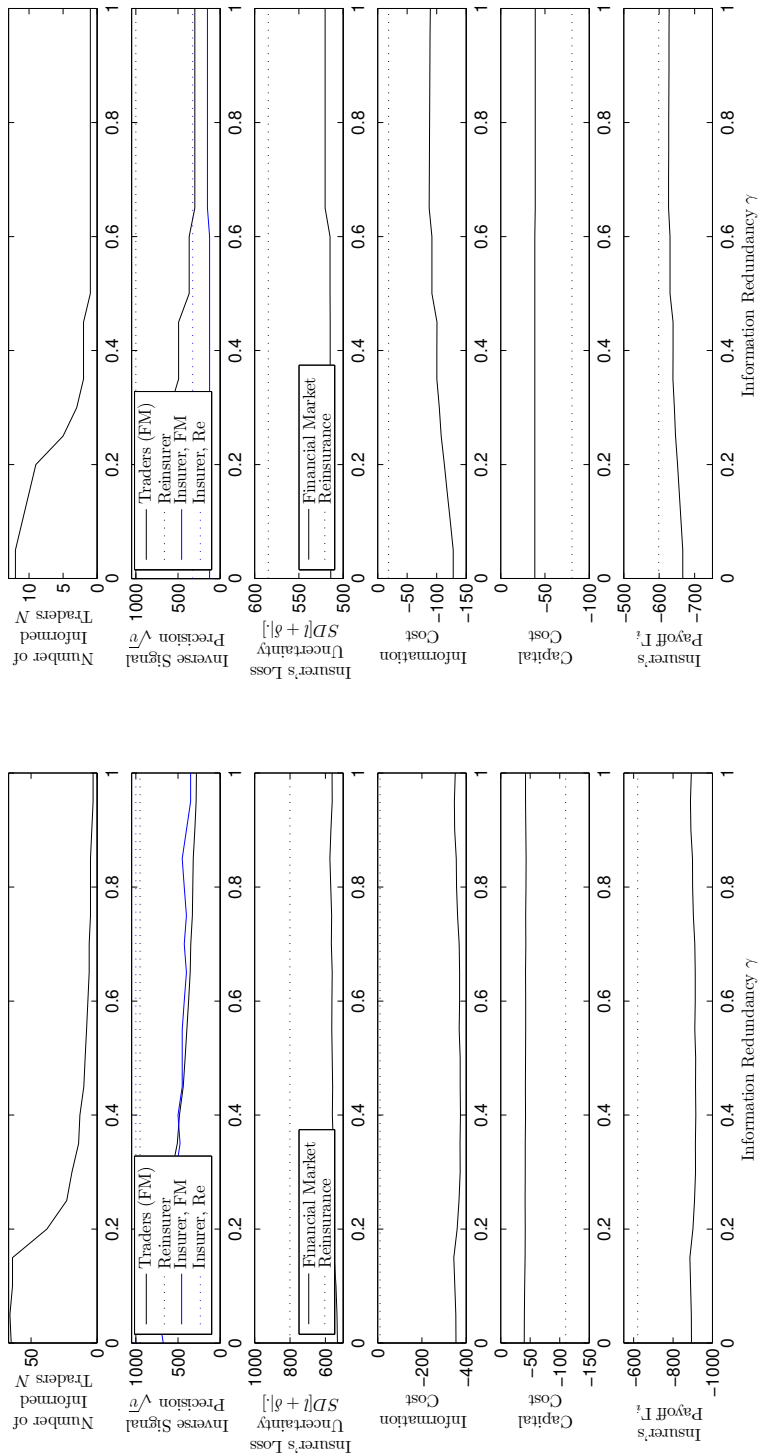

(a) High insurer information acquisition costs ($c_i = 20m$).

(b) Low insurer information acquisition costs ($c_i = 1m$).

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Figure 12: Information production by the insurer can alleviate the negative impact of high liquidity trading variability on the financial market.

Panel a shows the solution of the model when the variability of liquidity trading is high ($\sqrt{v_z} = 5m$) and the insurer is also able to acquire information, albeit at a high variable cost ($c_i = 20m$). Panel b considers a situation where the insurer's variable information acquisition cost is low ($c_i = 1m$).

(a) High liquidity trading variability, high insurer information acquisition costs ($\sqrt{v_z} = 5m$, $c_i = 20m$).

(b) High noise liquidity variability, low insurer information acquisition costs ($\sqrt{v_z} = 5m$, $c_i = 1m$).