Why Have Exchange-Traded Catastrophe Instruments Failed to Displace Reinsurance?

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Abstract

Financial markets can draw on a larger, more liquid, and more diversified pool of capital than the equity of reinsurance companies, yet they have failed to displace reinsurance as the primary risk-sharing vehicle for natural catastrophe risk. We show that such failure can be explained by differences in information gathering incentives between financial markets and reinsurance companies. Using a simple model of an insurance company that seeks to transfer a fraction of its risk exposure through financial markets or traditional reinsurance, we find that the supply of information by informed traders in financial markets may be excessive relative to its value for the insurance company, causing reinsurance to be preferred. Whether traditional reinsurance or financial markets dominate depends on the information acquisition cost structure and on the degree of redundancy in the information produced. Limits on the ability of informed traders to take advantage of their information make the use of financial markets more likely.

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Although the first reinsurance contract appeared in maritime shipping in Genoa in 1370, professional reinsurance companies did not emerge until 1842, with the founding of the Cologne Reinsurance Company following a catastrophic fire in Hamburg in 1842.[1] For over a century, professional reinsurance companies have been the preferred vehicle used by insurance companies to shed part of their catastrophe risk exposure.

Recently, traditional catastrophe reinsurance—viewed as an institutional vehicle to transfer catastrophe risk—has 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 his 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. The author explains these phenomena mainly by the inefficiencies that characterize the supply of capital to reinsurance companies and by these companies' excessive market power. According to Doherty (1997), 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).

The 1990s saw the development of a whole series of exchange-traded and over-the-counter catastrophe risk products. Catastrophe derivatives were first introduced on the Chicago Board of Trade (CBOT) in 1992. These exchange-traded derivatives were based on underlying indexes that reflected insurance property losses. They consisted primarily of futures and options written on futures contracts. Due to low interest, these contracts were replaced in 1995 by catastrophe spread options on loss indexes provided by the Property Claim Services (PCS); these options themselves were withdrawn in 2000. There was also low interest in the catastrophe index options traded on the Bermuda Commodities Ex-

[1] An overview of the history of the reinsurance industry can be found in Swiss Re (2002).

change, a dedicated exchange that opened in late 1997. Trading was suspended in August 1999, and the exchange eventually was liquidated.[2] Although *off-exchange, privately placed* catastrophe bonds, first introduced in 1994 by Hannover Re, have been more successful, their share of the reinsurance market remains limited: at the end of 2004, these bonds' outstanding risk capital represented less than 10% of total insured losses (Sigma, 2006).

Insurance, reinsurance, and other companies and institutions spend large amounts of money analyzing catastrophe risk. In this study, we show that differences in information gathering incentives between financial markets and reinsurance companies can explain why, over a decade after the introduction of the first catastrophe instruments, financial markets have not displaced reinsurance—despite the latter's alleged inefficiencies—as the primary risk-sharing vehicle for natural catastrophe risk. We consider a simple model where an insurance company seeks to transfer a fraction of its natural catastrophe risk exposure either through the financial market or through traditional reinsurance, selecting the form of risk transfer that has the lowest cost. Better information about the exposure decreases the amount of capital that must be held by the insurance company, either for regulatory reasons or for risk management purposes. Information acquisition—whether by the reinsurer or by informed traders in the financial market—is costly, and the cost of the information produced ultimately is borne by the insurer. Building on the Subrahmanyam and Titman (1999) model of the choice between private and public equity, we characterize the optimal information acquisition policy of informed traders and the reinsurer. We find that the financial market may display a Hirshleifer (1971) effect in the sense that the production of information by informed traders is excessive relative to its value for the insurance company. Not wishing to pay the cost of excessive information acquisition, the insurer favors reinsurance over the financial market.

The preceding is predicated on the fact that agents can and do acquire information about catastrophe risk. Is this the case? RMS, one of three leading specialized catastrophe

[2] A possible explanation is that market makers did not wish to make a market in which there was so little trading. Such explanation begs the obvious question of why there should have been so little trading in the first place. The answer suggested by our analysis is that adverse selection on such markets is so severe as to make excessive any discount necessary to induce participation by liquidity traders.

risk modeling firms, reports having over 400 clients among "insurers, reinsurers, trading companies, and other financial institutions." In a private communication, a member of the risk management department of Swiss Re, the world's largest 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).*

On a related note, Roll (1984) provides evidence consistent with futures traders' ability to forecast—that is, to acquire information about—weather-related phenomena.[3]

The argument we have made for catastrophe instruments can also be made for securities such as shares and numerous currency, interest-rate, and commodity derivatives. Yet, such securities are traded on exchanges. What distinctive features of catastrophe risk makes excessive information acquisition a problem for catastrophe instruments but not for shares? We believe that the key differences are the information acquisition *cost structure* and the *degree of redundancy* in the information produced.

Consider the information acquisition cost structure first. Our model distinguishes between fixed and variable information acquisition costs. Agents can acquire a signal of a given quality at a fixed cost; they can refine the quality of the signal by incurring further, variable costs. We find that the size of the fixed cost and the relative magnitude of the fixed and variable costs—i.e., the degree of convexity in the information acquisition cost structure—are key determinants of the preferred form of risk transfer. When the fixed cost

[3] The acquisition of information is clearly easier for some catastrophes than for 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.

is large, information acquisition by multiple traders in the financial market is too costly, and reinsurance is preferred. When the fixed cost is large compared to the variable cost, centralized information acquisition by the reinsurer is more efficient than decentralized information acquisition in the financial market, again favoring reinsurance. In contrast, when information acquisition costs are highly convex, information acquisition by several traders in the financial market is more efficient, and the financial market is preferred. Thus, large fixed information acquisition costs constitute a key explanation for the failure of exchange-traded catastrophe instruments.[4]

The second key determinant of the preferred form of risk transfer is the degree of redundancy in the information produced. To motivate the concept of information redundancy, contrast two phenomena, one well-understood and the other much less so. An example of the former may be the profitability of a firm; an example of the latter may be global warming. If it were possible to aggregate all available information about one and the other phenomena, for example through trading in a financial market, it is likely that much less uncertainty would remain about the first phenomenon than the second. The same holds true of financial securities whose payoffs depend on these phenomena. More concretely, the value of a share traded on a stock market is likely to be estimated much more precisely than the value of a catastrophe instrument such as a catastrophe option traded on an option market.[5] This means that much more of the information about the option is redundant than about the share. Indeed, if the information were not redundant, gathering increasing amounts of information would progressively reduce and eventually

[4]Fixed information acquisition costs for a given catastrophe are in the order of several million dollars (see Section 3).

[5]This is consistent with shares having higher volatility than insurance-linked securities. To see this, recall the relation

$$\begin{aligned} \operatorname{var}[x] &= E[\operatorname{var}[x|y]] + \operatorname{var}[E[x|y]] \\ \Leftrightarrow \operatorname{var}[E[x|y]] &= \operatorname{var}[x] - E[\operatorname{var}[x|y]] \end{aligned}$$

Let x denote a given payoff and y information about that payoff. The price of a claim on the payoff is of the form $E[x|y]$. Better information about the payoff implies lower uncertainty about that payoff (lower $E[\operatorname{var}[x|y]]$) and, from the relation above, a more volatile price (higher $\operatorname{var}[E[x|y]]$). The intuition is that better information makes the posterior more distinguishable from the prior, therefore more volatile.

altogether eliminate the uncertainty about the value of the option.[6]

To investigate the role of information redundancy in detail, we assume that the information regarding insured losses that a reinsurer or a trader in the financial market can gather contains both a systematic and an idiosyncratic error component. We find that the insurer's preference for one source of risk transfer over the other depends crucially on the relative importance of these two components. If the systematic error component is large, then having numerous traders in the financial market produce information is not very valuable: since much of that information is redundant, aggregate uncertainty about the loss remains large. Reinsurance therefore dominates in this case. In contrast, when the systematic component is small, information acquisition by numerous traders in the financial market is valuable: since traders' errors are mostly uncorrelated, information aggregation in the financial market makes for drastically reduced aggregate uncertainty about the loss. Such a drastic reduction cannot be achieved through reinsurance, and the financial market therefore dominates. The large systematic error component in insured loss estimates therefore constitutes a second key explanation for the failure of exchange-traded catastrophe instruments.[7]

Besides the information acquisition cost structure and information redundancy, several factors affect the insurer's choice between financial markets and reinsurance. Generally, financial markets dominate if there are tight limits on the ability of informed traders to profit from their information, thereby decreasing traders' incentives to acquire information.

[6] See the model in Section 1 for formal details. On an informal level, redundancy in information captures the extent of "thinking alike" that 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.

[7] Recent experience indicates that the systematic error component in the estimates of losses associated with natural catastrophes is indeed large. For example, in the case of hurricane Katrina in 2005, all major loss prediction models appear to have omitted the same factors. According to Swiss Re (2006), "what *the models* didn't predict was the storm surge [...], the breaching of the now deemed inadequate levee system protecting New Orleans [...] and the ensuing flood. [...] *All three catastrophe modellers* have looked at the impact of the increased frequency of hurricanes, while issues such as storm surge and flooding, demand surge and wind damage functions have either been introduced or improved." (Emphasis added.)

For example, if there are few liquidity traders in the market, informed traders are not able to "camouflage" their trades. In contrast, reinsurance dominates when the standard deviation of losses is large. This is because informed traders perceive large profit opportunities, enter the financial market in large numbers, and acquire large amounts of information. Since the cost of gathering information is borne by the insurer, the financial market is more costly than reinsurance.

There is an extensive literature on the use of 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 their lack of exposure to moral hazard and to default risk (Doherty, 1997, and Lakdawalla and Zanjani, 2006). In view of the very limited success of financial markets in transferring catastrophe risk, a number of potential explanations have been investigated: transactions costs, basis risk, and behavioral factors. Froot (2001) rules out the first. Harrington and Niehaus (1999) and Cummins, Lalonde, and Phillips (2004) find that using standardized contracts carries little basis risk for large insurers. Bantwal and Kunreuther (2000) suggest that ambiguity aversion, loss aversion, and uncertainty avoidance may account for the reluctance of investment managers to invest in catastrophe bonds. Barrieu and Loubergé (2006) 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. Unlike Bantwal and Kunreuther (2000) and Barrieu and Loubergé (2006), whose explanations for the limited use of financial markets are demand-based, ours is supply-based.

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.[8] Our paper extends this literature by considering the role of two hitherto neglected factors: the information acquisition cost structure and the degree of redundancy in the information produced. As argued above, and as will be shown below, these are key determinants of the preferred form of risk transfer.

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

The paper proceeds as follows. Section 1 presents our model of an insurer that seeks to transfer a fraction of the risks he has insured either through reinsurance or using the financial market, selecting the form of risk transfer that has the lowest cost. Section 2 investigates the effect of information redundancy on the insurer's preferred risk transfer vehicle. Section 3 numerically analyzes the impact of the main model parameters on the insurer's decision. Sections 4 concludes.

1 The Model

We consider an insurer that has insured losses represented by an asset of an uncertain (negative) value. The insurer has to choose between ceding risk to the financial market or to a reinsurer.[9] We assume that the insurer can cede no more than a fraction $\overline{\tau} < 1$ of the losses he has insured.[10]

In order to motivate the ceding of risk, we assume that the insurer's access to information is limited and that he has higher net cost of capital than does the reinsurer. The insurer therefore cedes risk for two reasons. The first is to replace his own, more expensive capital by the cheaper capital of the reinsurer or the "free" capital of the financial market (the capital of the financial market is free in the sense of having a net cost of zero).

The second reason is to induce the party to whom risk has been ceded, be it the informed traders in the financial market or the reinsurer, to incur the cost of improving the quality of the information, either in order to profit from informed trading or in order to economize on costly capital. The information 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 is ultimately borne by the insurer, either directly through the reinsurance premium or indirectly through a discount on the price of

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

[10] Moral hazard, adverse selection, and regulation generally preclude complete reinsurance.

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.

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 this section describes the details of the model. Section 1.1 describes the underlying information structure. Section 1.2 characterizes the structure of the financial market and informed traders' optimal information gathering decision. Section 1.3 presents the reinsurer's optimal information gathering decision. Section 1.4 derives the insurer' expected payoff for both risk transfer mechanisms.

1.1 The Information Structure

We assume that insured losses are represented by an asset that has value $\bar{l}+\delta$, with $\bar{l}<0$ and $\delta \sim N(0, v_\delta)$. Each agent s, which can be either a reinsurance company r or an informed trader n, $n=1,\ldots,N$, can acquire information $i_s = \delta + \sqrt{v_s}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_s\right)$, $0 \leqslant \gamma \leqslant 1$. We assume $\xi \sim N(0,1)$, $\epsilon_s \sim N(0,1)$, $\operatorname{cov}(\delta,\xi) = \operatorname{cov}(\delta,\epsilon_s) = \operatorname{cov}(\xi,\epsilon_s) = \operatorname{cov}(\epsilon_s,\epsilon_t) = 0$ for $s \neq t$.

The error in the information about losses 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

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

We refer to γ as the degree of redundancy in the information acquired. To provide some justification for our choice of terminology, consider the average error term 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

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

Using that variance as a proxy for the uncertainty that remains once the information across all agents has been aggregated, we see that the larger γ, the smaller the decrease in aggregate uncertainty as more agents contribute information, i.e., the larger γ, the larger the redundancy in the information across agents.

To provide some intuition for the role of γ in the model, consider the two extreme cases $\gamma = 0$ and $\gamma = 1$. In the former case, the variance of the average error term disappears for $\gamma = 0$ as $N \to \infty$: there is no aggregate uncertainty when a large enough number of agents can be called upon to contribute their information. In the latter, the variance of the average error term is unaffected by N: aggregate uncertainty remains regardless of the number of agents contributing information. We view the former case as representing well understood risks such as mortality risk (assuming new diseases such as AIDS do not render established mortality tables obsolete). Whilst no agent alone has a complete picture of the risk, all agents together do. We view the latter case as representing those risks that are still poorly understood, such as some forms of catastrophe risk. As mentioned in the introduction, there is evidence that the systematic error component in the estimates of losses associated with natural catastrophes—the redundancy in the information—is indeed large.

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 $c\left(\overline{v}/v_s - 1\right)$. The agent's total cost of acquiring information is therefore $c\left(\overline{v}/v_s - 1\right) + k$.[11] Note that information acquisition by agent s decreases the

[11] As in Subrahmanyam and Titman (1999; p. 1060), and in the line of Grossman and Stiglitz (1980),

variance of the entire error term, reducing both correlated and uncorrelated errors, in the same proportion.

Note also that we assume that the reinsurer and informed traders can acquire the same information, at the same cost. In fact, given modeling expertise acquired and customer data accumulated over decades of operation, reinsurers may well be endowed with better information or have lower information acquisition costs than even sophisticated traders in financial markets. However, since our purpose is to explain the dominance of reinsurance over the financial market, we do not wish to build an advantage for reinsurance into the assumptions of the model.

1.2 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 on the financial market.[12] 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.[13] 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

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. We choose the formulation $c(\overline{v}/v_s - 1) + k$ for tractability.

[12]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).

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

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 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

$$Q = x_n + \sum_{\substack{m=1 \\ m \neq n}}^{N} \kappa i_m + z = x_n + \sum_{\substack{m=1 \\ m \neq n}}^{N} \kappa\left(\delta + \sqrt{v}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_m\right)\right) + z \tag{3}$$

denotes the total order flow received by the market maker, including liquidity trader demand z. Note that we consider a symmetric equilibrium, in which κ and v are the same for all traders.

Naturally, trader n takes the demand and the (inverse) quality of the information of the other 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

$$\begin{aligned} \max_{x_n} E\left[x_n\left[\overline{\tau}\overline{l} + \overline{\tau}\delta - P\right]|i_n\right] &\equiv \max_{x_n} E\left[x_n\left[\overline{\tau}\delta - \zeta Q\right]|i_n\right] \\ &\equiv \max_{x_n} E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1 \\ m \neq n}}^{N} \kappa i_m + z\right)\right]|i_n\right] \end{aligned} \tag{4}$$

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

$$x_n = \kappa_n i_n = \kappa_n\left(\delta + \sqrt{v_n}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_n\right)\right) \tag{5}$$

where

$$\kappa_n = \frac{1}{2\zeta}\frac{\overline{\tau}v_\delta - \zeta\left(N-1\right)\kappa\left(v_\delta + \gamma^2\sqrt{v_n}\sqrt{v}\right)}{v_\delta + v_n} \tag{6}$$

In choosing v_n, trader n uses x_n obtained in (5) to solve

$$\max_{v_n} E\left[E\left[x_n\left[\overline{\tau}\delta - \zeta\left(x_n + \sum_{\substack{m=1 \\ m \neq n}}^{N} \kappa i_m + z\right)\right]|i_n\right]\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{7}$$

subject to the constraint $0 \leq v_n \leq \overline{v}$. In so doing, trader n treats κ, ζ, and v as constant. We show in the appendix that in a symmetric equilibrium ($v_n = v$), we have

$$\zeta = \frac{\overline{\tau} v_\delta \sqrt{N\left(v_\delta + v\right)}}{\sqrt{v_z}\left[(N+1)\, v_\delta + \left(2 + (N-1)\gamma^2\right) v\right]} \tag{8}$$

$$\kappa = \sqrt{\frac{v_z}{N(v_\delta + v)}} \tag{9}$$

and that the first-order condition for v is

$$\frac{\overline{\tau}\left(2 + (N-1)\gamma^2\right)\sqrt{v_z} v_\delta}{2\sqrt{N}\sqrt{v_\delta + v}\left[(N+1)\, v_\delta + \left(2 + (N-1)\gamma^2\right) v\right]} = c\frac{\overline{v}}{v^2} \tag{10}$$

Consider first the price impact of order flow, ζ in (8). 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 $N < N^*$.[14] 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.[15]

This last effect is reflected in the aggressiveness with which informed traders respond to information, κ in (9): 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 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).

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

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

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

Now consider the first-order condition (10). 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.[16] 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.[17] Note also that since the left hand side of (10) 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 ceded, $\overline{\tau}$, 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.[18]

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

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

[16]To see this, note that

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

[17]To see this, note that

$$\begin{aligned}&\frac{\partial}{\partial N}\left(\frac{2+(N-1)\gamma^2}{\sqrt{N}\left[(N+1)v_\delta + (2+(N-1)\gamma^2)\,v\right]}\right)\\ = \; & -\frac{\left(\left(2-\gamma^2\right)+\left(6-4\gamma^2\right)N + N^2\gamma^2\right)v_\delta + \left(2+(N-1)\gamma^2\right)^2 v}{2N^{\frac{3}{2}}\left[(N+1)v_\delta + (2+(N-1)\gamma^2)\,v\right]^2} < 0\end{aligned}$$

[18]The impact of uncertainty about the loss v_δ on the information acquired is ambiguous, since

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

As one would expect, this profit is increasing in the fraction of risk ceded, $\overline{\tau}$, 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, v_δ.[19] 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

$$Q = \kappa \sum_{n=1}^{N} i_n + z = N\kappa\left(\delta + \sqrt{\overline{v}}\gamma\xi\right) + \kappa\sqrt{\overline{v}}\sqrt{1-\gamma^2}\sum_{n=1}^{N}\epsilon_n + z \tag{12}$$

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, $N\left(c(\overline{v}/v - 1) + k\right)$.[20] The issue price therefore equals

$$I \equiv \overline{\tau}\overline{l} - N\left(c\left(\frac{\overline{v}}{v} - 1\right) + k\right) \tag{13}$$

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

[19] We have

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

[20] Liquidity traders' expected losses equal $E((P - \overline{\tau}\overline{l})z) = E(\zeta Q z) = \zeta v_z$. Using (8) and $\Pi_f(N) = 0$, we have

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

1.3 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. Thus, in an unregulated environment, a higher λ would reflect more cautiousness on the part of the reinsurer, while in a regulated environment, it would reflect more stringent capital requirements.

The reinsurer's capital has positive net cost because of information and incentive considerations (Froot, Scharfstein, and Stein, 1993; Froot and O'Connell, 1997; Froot and Stein, 1998; Gron and Winton, 2001). Note that, while capital is needed in the case of the financial market too, where it takes the form of margin requirements, it has zero net cost in that case. Indeed, because it is deposited in a margin account maintained by a clearinghouse rather than invested in the shares issued by a reinsurance company, capital in the financial market involves neither information nor incentive considerations.[21]

As mentioned in Section 1.1, we assume that the reinsurer can acquire the same information as an informed trader, at the same cost. The problem solved by the reinsurer who is assumed to reinsure a fraction $\overline{\tau}$ of insured losses $\bar{l}+\delta$ is

$$\begin{aligned} & \max_{v_r} \overline{\tau}\left(\bar{l} - \lambda a_r SD\left[\delta \left| \delta + \sqrt{v_r}\left(\gamma\xi + \sqrt{1-\gamma^2}\epsilon_r\right)\right.\right]\right) - c\left(\frac{\overline{v}}{v_r} - 1\right) - k \\ = \; & \max_{v_r} \overline{\tau}\left(\bar{l} - \lambda a_r \left[v_\delta - \frac{v_\delta^2}{v_\delta + v_r}\right]^{\frac{1}{2}}\right) - c\left(\frac{\overline{v}}{v_r} - 1\right) - k \qquad (14) \end{aligned}$$

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,

[21] The net cost of capital a_r includes any discount at which the reinsurance company's shares are issued. Any such discount is likely to be smaller than the discount on the catastrophe instruments considered in Section 1.2, because of diversification within the reinsurance company. This is the direct analogue to Subrahmanyam (1991) and Gorton and Pennacchi's (1993) comparison of individual stocks and stock market indices. The cost a_r can also be increased to include any economic rent the reinsurer may earn.

as represented by λ times the conditional standard deviation, is decreasing in the quality of the information acquired, $1/v_r$.

In the case of an interior solution, problem (14) has first-order condition

$$\frac{\overline{\tau}\lambda a_r}{2}\frac{v_\delta^{\frac{3}{2}}}{(v_\delta+v_r)^{\frac{3}{2}}\,v_r^{\frac{1}{2}}}=c\frac{\overline{v}}{v_r^2} \tag{15}$$

Solving and imposing the constraint $v_r \leq \overline{v}$ yields

$$v_r=\min\left[\overline{v},\frac{v_\delta\phi}{v_\delta-\phi}\right],\quad \phi\equiv\left(\frac{2c\overline{v}}{\overline{\tau}\lambda a_r}\right)^{\frac{2}{3}} \tag{16}$$

Observe that more variable losses, v_δ, induce more information acquisition by the reinsurer. In contrast, since there is a single reinsurer, the degree of information redundancy γ has no impact on the reinsurer's optimal information acquisition strategy. Observe also that since $\partial v_r/\partial\phi \geq 0$, a greater 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. 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 ceded, $\overline{\tau}$, and in the starting quality of the information, $1/\overline{v}$.

It is instructive to compare v_r in (16) with v in (10). It is possible to obtain 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.

1.4 The Insurer

Having analyzed the information gathering incentives of informed traders in the financial markets and of the reinsurer, we can now determine the expected cost to the insurer of using financial markets or reinsurance to transfer risk.

From (13), 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, $I = \overline{\tau}\bar{l} - N\left(c\left(\overline{v}/v - 1\right) + k\right)$. 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 financial market for ceding risk is

$$\begin{aligned}\Gamma_{i,f} &= (1-\overline{\tau})\,\bar{l} - \lambda a_i\,(1-\overline{\tau})\,SD\left[\delta\,|Q\right] + \overline{\tau}\bar{l} - N\left(c\left(\frac{\overline{v}}{v} - 1\right) + k\right) \qquad (17)\\ &= \bar{l} - \lambda a_i\,(1-\overline{\tau})\,\sqrt{v_\delta}\left[1 - \frac{N v_\delta}{(N+1)v_\delta + \left(2 + (N-1)\gamma^2\right)v}\right]^{\frac{1}{2}} - N\left(c\left(\frac{\overline{v}}{v} - 1\right) + k\right)\end{aligned}$$

where the second equality follows from (9) and (12), v is the solution to (10), and N is obtained from the zero profit condition $\Pi_f(N) = 0$. Note that the price is more informative ($SD[\delta|Q]$ 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 $\bar{l}$, plus the reinsurer's capital cost, plus his information acquisition cost, i.e., $\overline{\tau}\bar{l} - \lambda a_r \overline{\tau} SD\left[\delta\,|i_r\right] - c\left(\overline{v}/v_r - 1\right) - k$. The benefit is again a reduction in the required amount of capital. Hence, the insurer's expected payoff from ceding risk to the reinsurer is

$$\begin{aligned}\Gamma_{i,r} &= (1-\overline{\tau})\,\bar{l} - \lambda a_i\,(1-\overline{\tau})\,SD\left[\delta\,|i_r\right] + \overline{\tau}\bar{l} - \lambda a_r \overline{\tau} SD\left[\delta\,|i_r\right] - c\left(\frac{\overline{v}}{v_r} - 1\right) - k\\ &= \bar{l} - \lambda\left[a_i\,(1-\overline{\tau}) + a_r\overline{\tau}\right]\sqrt{v_\delta}\left[1 - \frac{v_\delta}{v_\delta + v_r}\right]^{\frac{1}{2}} - c\left(\frac{\overline{v}}{v_r} - 1\right) - k \qquad (18)\end{aligned}$$

where v_r is given by (16).

2 A First Look at the Role of Information Redundancy

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 in order to provide some intuition and illustrate some of the tradeoffs involved in the insurer's choice, we may consider the two polar cases $\gamma = 0$ and $\gamma = 1$, with $k = 0$ and N therefore large.

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 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 and therefore has no need for capital, so that

$$\Gamma_{i,f} = \overline{l} \tag{19}$$

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

$$\Gamma_{i,r} = \overline{l} - \lambda \left[a_i \left(1 - \overline{\tau}\right) + a_r \overline{\tau}\right] \sqrt{v_\delta} \left[1 - \frac{v_\delta}{v_\delta + v_r}\right]^{\frac{1}{2}} - c \left(\frac{\overline{v}}{v_r} - 1\right) \tag{20}$$

Hence, regardless of whether the reinsurer chooses to acquire information beyond $1/\overline{v}$ or not, the insurer's payoff from using reinsurance is *lower* than that from using the financial market. Thus, as in Subrahmanyam and Titman (1999), when the correlated error term disappears ($\gamma = 0$), the financial market reveals the information about δ very precisely, and public financing dominates private financing (reinsurance in our case).

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

$$\Gamma_{i,f} = \overline{l} - \lambda a_i \left(1 - \overline{\tau}\right) \sqrt{v_\delta} \left[1 - \frac{v_\delta}{v_\delta + \overline{v}}\right]^{\frac{1}{2}} \tag{21}$$

The expected payoff from using reinsurance does not depend on γ, and is therefore still given by (20). 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 (20) with $v_r = \overline{v}$, i.e., one has

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

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 the financial market. On the other hand, the zero net cost of capital of the financial market favors the financial market 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.

3 Determinants of the Preferred Form of Risk Transfer

In order to gain greater insights into how the different parameters affect the preferred form of risk transfer, we solve the model numerically, computing the insurer's expected payoff from transferring risk both to the financial market and to the reinsurer. 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 (10), 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 (11), given their optimal information acquisition strategy v, is nonnegative. Finally, given N and v, the insurer's payoff is computed using (17). 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 (16). The insurer's payoff is then obtained by inserting the optimal v_r into (18).

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): $\bar{l} = -500m$, $\sqrt{v_\delta} = 1,600m$, $\sqrt{\overline{v}} = 1,000m$, $\overline{\tau} = 0.5$, $a_r = 0.05$, $k = 5m$, and $c = 6m$. 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 $\sqrt{\overline{v}} = 1,000m$ 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), we set $a_i = 0.06$.[22] Finally, reflecting 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 a near halving of the uncertainty about losses.

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, $\sigma \equiv \sqrt{v}$ for the financial market and $\sigma_r \equiv \sqrt{v_r}$ for reinsurance, (3) the (inverse) quality of the information available to the insurer, $SD\left[\delta\,|Q\right]$ for the financial market and $SD\left[\delta\,|i_r\right]$ 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, $\lambda a_i\left(1-\overline{\tau}\right)SD[\delta|Q]$ for the financial market and $\lambda\left[a_i\left(1-\overline{\tau}\right)+a_r\overline{\tau}\right]SD[\delta|i_r]$ for reinsurance, and (6) the payoffs to the insurer from both forms of risk transfer, $\Gamma_{i,f}$

[22] 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.

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 ranges from about $50m$ for $\gamma = 0$ to about $20m$ for $\gamma = 1$. It represents the net impact of two effects. First, the capital cost for the fraction 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. Although the reinsurer acquires more precise information than individual informed traders in the financial market, for $\gamma < 0.5$, 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 ($\gamma > 0.5$), the opposite holds.

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 1), it does affect information production in the financial market and the cost of using it. The results in Figure 1 show that 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, an increase in γ causes total information acquisition costs to rise, but the quality of the information available to the insurer to deteriorate. This causes reinsurance to dominate 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 the larger information acquisition costs—the reinsurer's information production is much more efficient because it avoids duplication.

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 shows the solution of the model for $k = 0.1m$ (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).[23] Observe that for $\gamma < 0.75$, the number of informed traders in the financial market is much larger than previously 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 Figure 1 at about $30m$. Second, because the larger number of traders provides for better quality information, the financial market's capital cost advantage is higher than in the base case, ranging from $70m$ for $\gamma = 0$ to $30m$ for $\gamma = 0.75$. Observe also that for $\gamma < 0.6$, the financial market provides better information than reinsurance. In contrast to the situation in Figure 1, however, the extra information is worth the extra cost because of the low k.

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

[23] Other than those in the base case, not all the parameter values we use are realistic. We use many extreme values because such values have the merit of delivering stark results, thereby clearly illustrating the comparative statics of the model.

produces the second outcome. This makes the use of the financial market 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 a situation where the fixed cost k was much smaller than the variable cost c. Figure 3 shows the model's solution for the opposite situation, with $c = 0.12m$ and $k = 5m$. In this setting, the cost structure is such that 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 information provided by reinsurance is more precise than that provided by the financial market to such an extent that reinsurance also has a capital cost advantage over the financial market (despite the reinsurer's positive cost of capital a_r). Thus, for low c and large k, reinsurance strongly dominates the financial market for all γ.

The intuition that the ratio c/k constitutes a key determinant of the preferred form of risk transfer is confirmed in Figure 4, which considers the situation where both c and k are 50 times smaller than in the base case, i.e., setting $c = 0.12$ and $k = 0.1$. Note that except for very low values of γ, the quality of the information provided by reinsurance exceeds that provided by the financial market. Furthermore, and as in Figure 1, the total information acquisition cost is much higher for the financial market than for reinsurance. As a result, and as in the base case, reinsurance dominates the financial market for all γ.

The implication of Figures 2–4 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 concern. 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.

There is a widespread view that the presence of numerous hedgers and liquidity traders supports the use and development of financial markets.[24] In order to determine whether this is indeed the case, consider the effect of increasing the volatility of liquidity trader demand to $\sqrt{v_z} = 5$, five times its initial value, while keeping all other parameters as in the base case. The results are reported in Figure 5. 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 $\gamma > 0.6$, 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 $500m$, 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 implication is that in order for risk transfer through the financial market to be advantageous, it may be necessary to restrict rather than encourage the participation of liquidity traders in these markets. Limited liquidity trader participation may account for the relative success of off-exchange, privately placed catastrophe bonds mentioned in the introduction.

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 6, which uses $\sqrt{v_z} = 5$ and $k = 0.001m$, reveals that this is indeed the case. Observe that the financial market dominates reinsurance for

[24] See for example Cuny (1993).

$\gamma < 0.4$, i.e., for values of γ for which the number of traders is extremely large at almost 30,000, but none of the traders acquires information beyond $1/\overline{v}$. In spite of the fact that no trader acquires information beyond $1/\overline{v}$, for low γ, the large number of traders makes the information contained in the price extremely precise. This reduces the capital cost of using the financial market below that of using reinsurance. 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 6 is that when hedging 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 2–4, but the required values become more extreme, the larger $\sqrt{v_z}$. We view the present case as representative of share and bond markets for low γ.

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, $\sqrt{v_\delta}$, is small. Figure 7, which shows the solution of the model when the uncertainty about the loss is reduced to $\sqrt{v_\delta} = 250$, 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 to an increase in loss uncertainty, such a global warming, may constitute an opportunity rather than a threat for reinsurance companies.

Note that the small initial uncertainty about the loss causes the payoff from using the financial market in Figure 7 to be increasing in γ. The reason is that as γ increases, the fall 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.[25]

Contrasting Figures 1 and 2 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. Figure 8, which shows the model's solution for $\sqrt{\overline{v}} = 200$, reveals 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 is therefore not worth paying the cost k multiple times (the outcome in the financial market), and reinsurance dominates. Note that in spite of its lower information acquisition costs, in the situation considered in Figure 8, reinsurance provides significantly better information than the financial market: liquidity trading garbles the information conveyed by the price in the financial market. As a result, reinsurance's capital cost disadvantage is tiny.

Figure 9 reports the model's solution when the fraction of risk ceded is increased to $\overline{\tau} = 0.8$. As expected, a higher $\overline{\tau}$ stimulates information acquisition both for the financial market and for reinsurance. Interestingly, the increase in the information produced in the financial market occurs both through the number of traders (which, for low γ, increases from about 30 in the base case to over 45 here) and through the precision of the information that each trader acquires. The overall impact of the increased information acquisition is a sizable widening of the financial market's information cost disadvantage to over $200m$, with the consequence that reinsurance dominates even more clearly than in the base case. For instance, for $\gamma = 0$, the insurer is about $140m$ better off using reinsurance than using the financial market, versus about $90m$ in the base case. For $\gamma = 1$, the payoff differential has widened from about $130m$ to about $190m$.

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

[25]Further computations, not reported in a figure for brevity, reveal that for very large values of a_i, the insurer's payoff from using the financial market is decreasing in γ as it was in previous figures.

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 10, which shows the model's solution for $a_i = 0.2$. Although information production and the financial market's information cost disadvantage are the same as in the base case, the financial market's capital cost advantage differs. For $\gamma < 0.5$, the financial market provides better information than reinsurance, and the capital cost advantage is larger than in the base case. In contrast, for $\gamma > 0.5$, reinsurance provides better information than the financial market, and the capital cost advantage is much smaller than in the base case—for $\gamma = 1$, it even vanishes. Thus, in this example, although reinsurance still dominates for all γ, the financial market performs better than in the base case for $\gamma < 0.5$ and worse for $\gamma > 0.5$.

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 11, which shows the model's solution for $a_r = 0.3$, reveals that this is indeed the case. Observe that the financial market dominates for low γ, but that reinsurance still dominates for large γ. 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 example in Figure 11, the reinsurer spends over $50m$ in information acquisition costs. This significantly reduces the financial market's information cost disadvantage.

A prior catastrophe also depletes the capital of primary insurers. Figure 12 shows the model's solution if, following a catastrophe, both the insurer's and the reinsurer's capital cost increase significantly to $a_i = 0.36$ and $a_r = 0.3$, respectively, six times their value in the base case. Observe that although it still performs better than in the base case, the financial market does not do as well as in Figure 11. In particular, it does not dominate reinsurance for low γ. The reason is that, as was shown in Figure 10, 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 compared to the financial market.

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 15 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 $a_i = 0.3$ and $a_r = 0.36$, the situation considered in Figure 12. The fact that the financial market performs comparatively better than in the base case for low γ and worse 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. 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 12, reinsurance's capital cost increases to about $260m$, compared to $70m$ in the base case. For the financial market, the capital cost increases from about $30m$ to $170m$ for $\gamma = 0$, and from about $50m$ to about $310m$ for $\gamma = 1$—almost twice as much. The consequence is that for $\gamma = 0$, the financial market's capital cost advantage has widened compared to the base case, while for $\gamma = 1$, it has turned into a capital cost disadvantage.

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 ceded $\overline{\tau}$ tend to favor reinsurance. In contrast, a large variable cost of information acquisition c, large noise in the information acquired $\sqrt{\overline{v}}$, 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. Finally, 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 for low γ and reinsurance for large γ.

4 Conclusion

In this study, we use differences in information gathering incentives between financial markets and reinsurance companies to explain why financial markets have not displaced reinsurance as the primary risk-sharing vehicle for natural catastrophe risk, despite reinsurance's alleged inefficiency. We consider an insurance company that seeks to transfer a fraction of its natural catastrophe risk exposure either through the financial market or through traditional reinsurance. Analyzing the optimal information acquisition policy of informed traders and the reinsurer, we find that the financial market may display a Hirshleifer (1971) effect in the sense that the supply of information by informed traders is excessive relative to its value for the insurance company. Since the cost of the information produced ultimately is borne by the insurer, he favors reinsurance over the financial market.

Whether traditional reinsurance or the financial market is ultimately selected depends crucially on the information acquisition cost structure and on the degree of redundancy in the information produced. When fixed information acquisition costs are large, it is very costly to have several traders in the financial market acquire information, and reinsurance is preferred. When information acquisition costs are highly convex, however, decentralized information production is more efficient, and the financial market is preferred. When the degree of redundancy in the information is large, there is little value to the insurer in having several traders acquire information, and reinsurance is preferred. Conversely, when the degree of redundancy is small, having several traders acquire information is very valuable because it allows reducing residual risk drastically, and the financial market is preferred.

A further prediction of the model is that factors that limit informed traders' ability to profitably take advantage of their information—such as the presence of few liquidity traders only—should make the use of the financial market more likely. The limited extent of liquidity trading in private markets may therefore provide an explanation for the relative success of the private placement of securitized natural catastrophe risks among insurance companies, hedge funds and other institutional players. In contrast, factors that stimulate information acquisition by informed traders should favor reinsurance. One such factor is an increase in the uncertainty about losses. Thus, paradoxically, global warming and its detrimental impact on loss uncertainty may represent an opportunity for reinsurance companies, unless the financial market's expertise in modeling natural catastrophe risks improves.

This study could be extended along several dimensions. First, one could allow the insurer to use both reinsurance and the financial market. Second, one could explicitly account for the moral hazard issues that prevail in the reinsurance industry in order to assess whether the magnitude of the associated costs would be sufficient to reverse the conclusion that reinsurance tends to dominate the financial market. Third, one could construct a dynamic version of the model incorporating the learning process that takes place in the financial market and in the reinsurance industry in order to assess whether greater familiarity with the assessment of catastrophe risks could, over time, make the use of the financial market more viable. Finally, one could investigate whether there are differences in the degree of information redundancy across the various types of natural catastrophes—earthquakes, floods, hurricanes, windstorms—in order to assess whether some of these risks are more amenable to securitization and successful exchange trading than others.

Appendix

Determination of Optimal Demand x_n

Recall from (4) that trader n chooses his optimal demand x_n by solving

$$\max_{x_n} E\left[x_n\left[\overline{\tau}\delta-\zeta\left(x_n+\sum_{\substack{m=1\\m\neq n}}^{N}\kappa i_m+z\right)\right]|i_n\right] \tag{23}$$

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

$$\begin{aligned}&\max_{x_n} x_n\left[\overline{\tau}E\left[\delta|i_n\right]-\zeta\left(x_n+(N-1)\kappa E\left[\delta|i_n\right]+(N-1)\kappa\sqrt{v}\gamma E\left[\xi|i_n\right]\right)\right]\\ =\ &\max_{x_n} x_n\left[(\overline{\tau}-\zeta(N-1)\kappa)\frac{v_\delta}{v_\delta+v_n}i_n-\zeta x_n-\zeta(N-1)\kappa\gamma^2\frac{\sqrt{v_n}\sqrt{v}}{v_\delta+v_n}i_n\right]\end{aligned} \tag{24}$$

Differentiating with respect to x_n and solving yields

$$x_n=\frac{1}{2\zeta}\frac{\overline{\tau}v_\delta-\zeta\left(N-1\right)\kappa\left(v_\delta+\gamma^2\sqrt{v_n}\sqrt{v}\right)}{v_\delta+v_n}i_n \tag{25}$$

which is optimal demand (5) in the text.

Determination of the Optimal Information Acquisition Policy v_n

Recall from (7) that trader n chooses his optimal information acquisition policy v_n by solving

$$\max_{v_n} E\left[E\left[x_n\left[\overline{\tau}\delta-\zeta\left(x_n+\sum_{\substack{m=1\\m\neq n}}^{N}\kappa i_m+z\right)\right]|i_n\right]\right]-c\left(\frac{\overline{v}}{v_n}-1\right)-k \tag{26}$$

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

$$\begin{aligned}\max_{v_n}\quad & E\left[x_n\left[(\overline{\tau}-\zeta(N-1)\kappa)\frac{v_\delta}{v_\delta+v_n}i_n-\zeta x_n-\zeta(N-1)\kappa\gamma^2\frac{\sqrt{v_n}\sqrt{v}}{v_\delta+v_n}i_n\right]\right]\\ & -c\left(\frac{\overline{v}}{v_n}-1\right)-k\end{aligned} \tag{27}$$

From (25), we have

$$\frac{\overline{\tau} v_\delta - \zeta (N-1) \kappa \left(v_\delta + \gamma^2 \sqrt{v_n}\sqrt{v}\right)}{v_\delta + v_n} i_n = 2\zeta x_n \tag{28}$$

Hence, problem (27) becomes

$$\begin{aligned} & \max_{v_n} E\left[x_n \left[2\zeta x_n - \zeta x_n\right]\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \\ = & \max_{v_n} E\left[\zeta x_n^2\right] - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \end{aligned} \tag{29}$$

Substituting x_n from (25) and using the fact that $E[i_n^2] = v_\delta + v_n$ then yields

$$\max_{v_n} \frac{1}{4\zeta} \frac{\left(\overline{\tau} v_\delta - \zeta\kappa (N-1) \left(v_\delta + \gamma^2 \sqrt{v_n}\sqrt{v}\right)\right)^2}{v_\delta + v_n} - c\left(\frac{\overline{v}}{v_n} - 1\right) - k \tag{30}$$

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

$$\begin{aligned} & \frac{1}{4\zeta} \frac{\overline{\tau} v_\delta - \zeta\kappa(N-1) \left(v_\delta + \gamma^2 \sqrt{v_n}\sqrt{v}\right)}{\left(v_\delta + v_n\right)^2} \times \\ & \left(\zeta\kappa(N-1)\gamma^2 \frac{\sqrt{v}}{\sqrt{v_n}} (v_\delta + v_n) + \left(\overline{\tau} v_\delta - \zeta\kappa (N-1) \left(v_\delta + \gamma^2 \sqrt{v_n}\sqrt{v}\right)\right)\right) = c\frac{\overline{v}}{v_n^2} \end{aligned} \tag{31}$$

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

$$\kappa = \frac{\overline{\tau} v_\delta}{\zeta \left[(N+1) v_\delta + (2 + (N-1)\gamma^2) v\right]} \tag{32}$$

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

$$\zeta = \frac{\operatorname{cov}\left(\overline{\tau}\delta, Q\right)}{\operatorname{var}\left(Q\right)} = \frac{\overline{\tau} v_\delta \sqrt{N\left(v_\delta + v\right)}}{\sqrt{v_z} \left[(N+1) v_\delta + (2 + (N-1)\gamma^2) v\right]} \tag{33}$$

Inserting this expression into (32) then yields

$$\kappa = \sqrt{\frac{v_z}{N(v_\delta + v)}} \tag{34}$$

Setting $v_n = v$ for a symmetric equilibrium and substituting κ and ζ from (32) and (33), the first order condition (31) becomes

$$\frac{\overline{\tau}\left(2 + (N-1)\gamma^2\right)\sqrt{v_z} v_\delta}{2\sqrt{N}\sqrt{v_\delta + v}\left[(N+1) v_\delta + (2 + (N-1)\gamma^2) v\right]} = c\frac{\overline{v}}{v^2} \tag{35}$$

which is (10) in the text.

Determination of Expected Profit Π_f

From (29), given $v_n = v$, the trader's expected profit is given by

$$\Pi_f = E\left[\zeta x_n^2\right] - c\left(\frac{\overline{v}}{v} - 1\right) - k \tag{36}$$

Using (8) and (9), the first term can be rewritten as

$$\begin{aligned} E\left[\zeta x_n^2\right] &= \zeta\kappa^2\left(v_\delta + v\right) \\ &= \left(\frac{\overline{\tau} v_\delta \sqrt{N\left(v_\delta + v\right)}}{\sqrt{v_z}\left[\left(N+1\right)v_\delta + \left(2 + (N-1)\gamma^2\right)v\right]}\right)\left(\frac{v_z}{N(v_\delta + v)}\right)\left(v_\delta + v\right) \\ &= \frac{\overline{\tau}\sqrt{v_z}v_\delta\sqrt{v_\delta + v}}{\sqrt{N}\left[\left(N+1\right)v_\delta + \left(2 + (N-1)\gamma^2\right)v\right]} \end{aligned} \tag{37}$$

Inserting this expression into (36) yields (11).

References

Bantwal, Vivek J. and Howard C. Kunreuther, 2000, "A Cat Bond Premium Puzzle?" *Journal of Psychology and Financial Markets* 1, 76-91.

Barrieu, Pauline and Henri Loubergé, 2006, "Hybrid Cat-Bonds," Working Paper.

Boot, Arnoud W.A. and Anjan V. Thakor, 1993, "Security Design," *Journal of Finance* 48, 1349-1378.

Cummins, J. David, David Lalonde, and Richard D. Phillips, 2004, "The Basis Risk of Catastrophic-Loss Index Securities," *Journal of Financial Economics* 71, 77-111.

Cuny, Charles J., 1993, "The Role of Liquidity in Futures Market Innovations," *Review of Financial Studies* 6, 57-78.

D'Arcy, Stephen P. and Virginia Grace France, 1992, "Catastrophe Futures: A Better Hedge for Insurers," *Journal of Risk and Insurance* 59, 575-600.

DeMarzo, Peter M. and J. Darrell Duffie, 1999, "A Liquidity Based Model of Security Design," *Econometrica* 67, 65-99.

Diamond, Douglas W., 1984, "Financial Intermediation and Delegated Monitoring," *Review of Economic Studies* 51, 393-414.

Doherty, Neil A., 1997, "Innovations in Managing Catastrophe Risk," *Journal of Risk and Insurance* 64, 713-718.

Doherty, Neil A. and Harris Schlesinger, 2002, "Insurance Contracts and Securitization," *Journal of Risk and Insurance* 69, 45-62.

Durbin, David, 2001, "Managing Natural Catastrophe Risks: The Structure and Dynamics of Reinsurance," *Geneva Papers on Risk and Insurance* 26, 297-309.

Fama, Eugene F. and Kenneth R. French, 1997, "Industry Costs of Equity," *Journal of Financial Economics* 43, 153-193.

Froot, Kenneth A., 2001, "The Market for Catastrophe Risk: A Clinical Examination," *Journal of Financial Economics* 60, 529-571.

Froot, Kenneth A. and Paul J. G. O'Connell, 1997, "On the Pricing of Intermediated Risks: Theory and Application to Catastrophe Reinsurance," NBER WP 6011.

Froot, Kenneth A., David S. Scharfstein, and Jeremy C. Stein, 1993, "Risk Management: Coordinating Corporate Investment and Financing Policies," *Journal of Finance* 48, 1629-1658.

Froot, Kenneth A. and Jeremy C. Stein, 1998, "Risk Management, Capital Budgeting, and Capital Structure Policy for Financial Institutions: An Integrated Approach," *Journal of Financial Economics* 47, 55-82.

Fulghieri, Paolo and Dmitry Lukin, 2001, "Information Production, Dilution Costs, and Optimal Security Design," *Journal of Financial Economics* 61, 3-42.

Gorton, Gary and George Pennacchi, 1993, "Security Baskets and Index-Linked Securities," *Journal of Business* 66, 1-23.

Gorton, Gary and Andrew Winton, 2003, "Financial Intermediation," in *Handbook of the Economics of Finance* 1A, George Constantinides, Milton Harris, and René M. Stulz (eds.), Elsevier North-Holland, Amsterdam.

Gron, Anne and Andrew Winton, 2001, "Risk Overhang and Market Behavior," *Journal of Business* 74, 591-612.

Grossman, Sanford J. and Joseph E. Stiglitz, 1980, "On the Impossibility of Informationally Efficient Markets," *American Economic Review* 70, 393-408.

Harrington, Scott and Greg Niehaus, 1999, "Basis Risk with PCS Catastrophe Insurance Derivative Contracts," *Journal of Risk and Insurance* 66, 49-82.

Hirshleifer, Jack, 1971, "The Private and Social Value of Information and the Reward to Inventive Activity," *American Economic Review* 61, 561-574.

Holmström, Bengt and Jean Tirole, 1993, "Market Liquidity and Performance Monitoring," *Journal of Political Economy* 101, 678-709.

Jaffee, Dwight M. and Thomas Russell, 1997, "Catastrophe Insurance, Capital Markets, and Uninsurable Risks," *Journal of Risk and Insurance* 64, 205-230.

Kyle, Albert S., 1985, "Continuous Auctions and Insider Trading," *Econometrica* 53, 1315-1335.

Lakdawalla, Darius and George Zanjani, 2006, "Catastrophe Bonds, Reinsurance, and the Optimal Collateralization of Risk-Transfer," NBER WP 12742.

Milgrom, Paul R. and Robert J. Weber, 1982, "A Theory of Auctions and Competitive Bidding," *Econometrica* 50, 1089-1122.

Niehaus, Greg and Steven V. Mann, 1992, "The Trading of Underwriting Risk: An Analysis of Insurance Futures Contracts and Reinsurance," *Journal of Risk and Insurance* 59, 601-627.

Roll, Richard, 1984, "Orange Juice and Weather," *American Economic Review* 74, 861-880.

Sigma, 2006, "Natural Catastrophes and Man-made Disasters in 2005," Sigma, No 2/2006, Swiss Reinsurance Company, Zurich.

Subrahmanyam, Avanidhar, 1991, "A Theory of Trading in Stock Index Futures," *Review of Financial Studies* 4, 17-51.

Subrahmanyam, Avanidhar and Sheridan Titman, 1999, "The Going-Public Decision and the Development of Financial Markets," *Journal of Finance* 54, 1045-1082.

Swiss Re, 2002, *An Introduction to Reinsurance*, Swiss Re Technical Publishing, Zurich.

Swiss Re, 2006, *Restoring the Faith*, Swiss Re Group Knowledge & Records Management, New Articles Bulletin, July 1, 2006.

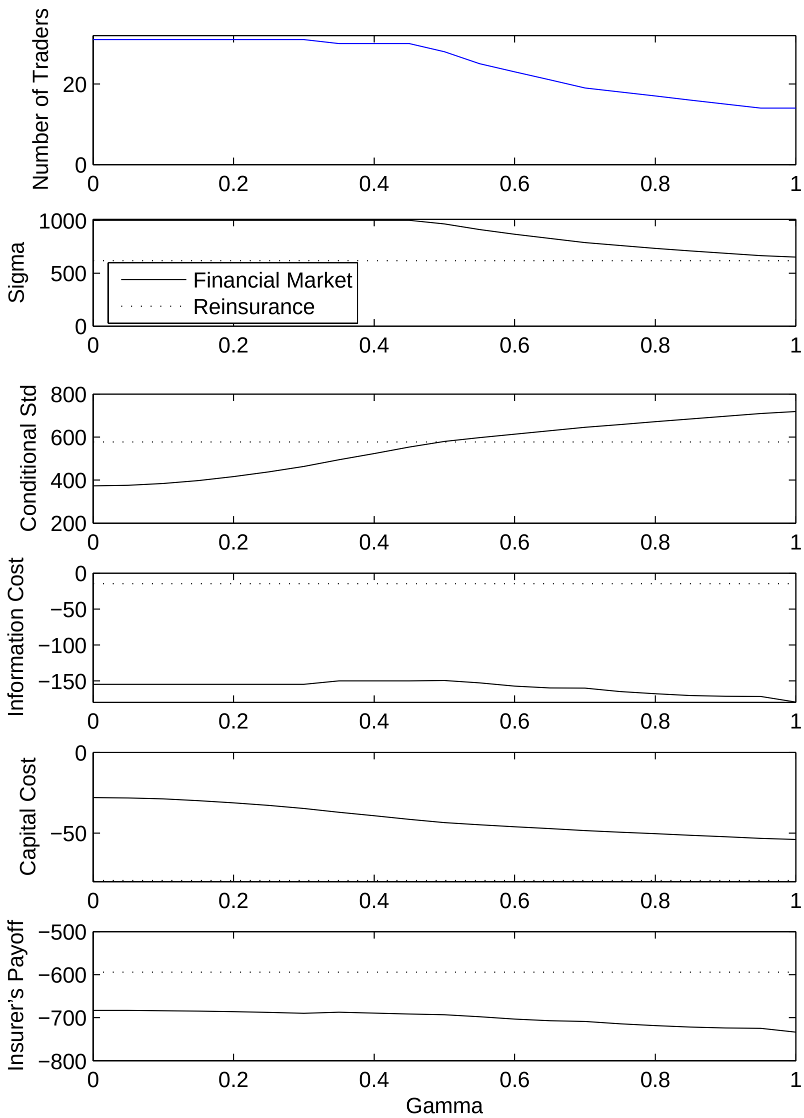

Figure 1: Solution of the model as a function of the degree of information redundancy γ for the base case parameter values $\bar{l} = -500m$, $\sqrt{v_\delta} = 1,600m$, $\sqrt{\overline{v}} = 1,000m$, $\sqrt{v_z} = 1m$, $\lambda = 2.5$, $\overline{\tau} = 0.5$, $a_i = 0.06$, $a_r = 0.05$, $k = 5m$, 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, $\sigma = \sqrt{v}$, and by the reinsurer, $\sigma = \sqrt{v_r}$. The third panel reports the (inverse) quality of the information available to the insurer, $SD[\delta|Q]$ for the financial market and $SD[\delta|i_r]$ for reinsurance. The fourth panel reports the total information acquisition cost, $N(c(\overline{v}/v - 1) + k)$ for the financial market and $c(\overline{v}/v_r - 1) + k$ for reinsurance. The fifth panel reports the total capital cost, $\lambda a_i (1 - \overline{\tau}) SD[\delta|Q]$ for the financial market and $\lambda[a_i(1 - \overline{\tau}) + a_r\overline{\tau}] SD[\delta|i_r]$ for reinsurance. The sixth panel shows the payoffs to the insurer from using the financial market and reinsurance, $\Gamma_{i,f}$ and $\Gamma_{i,r}$.

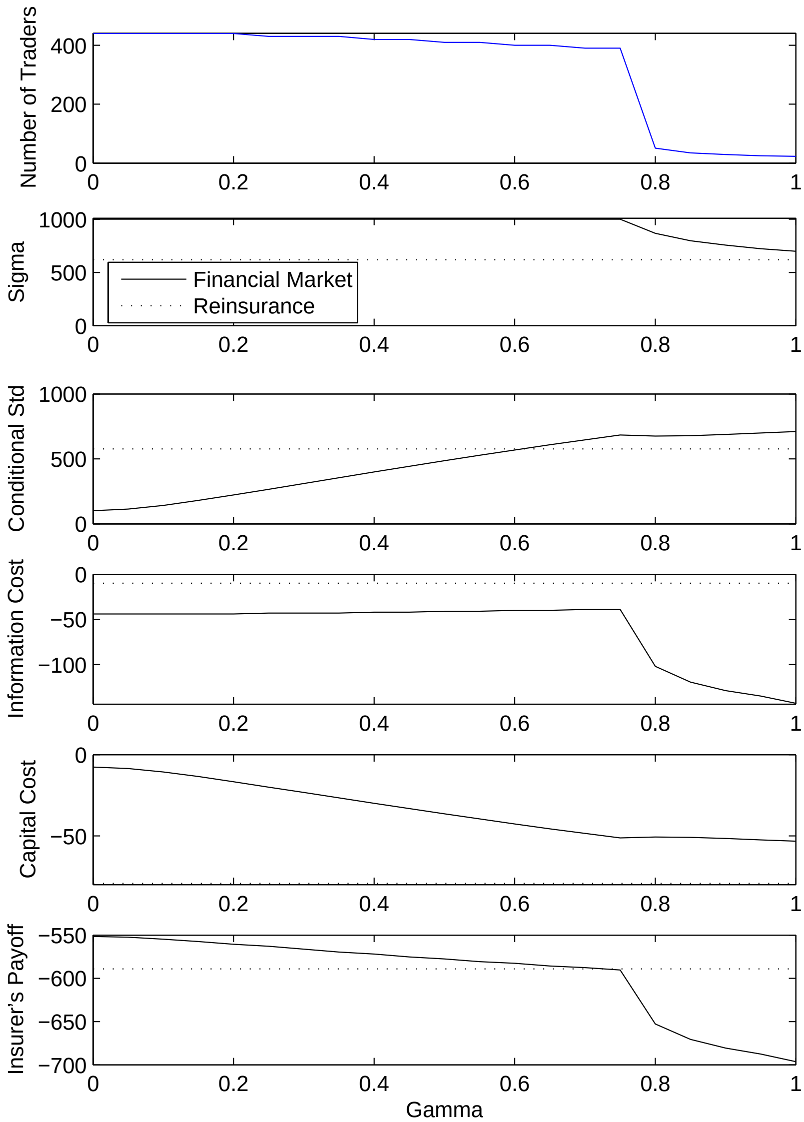

Figure 2: Solution of the model as a function of the degree of information redundancy γ with $k = 0.1$.

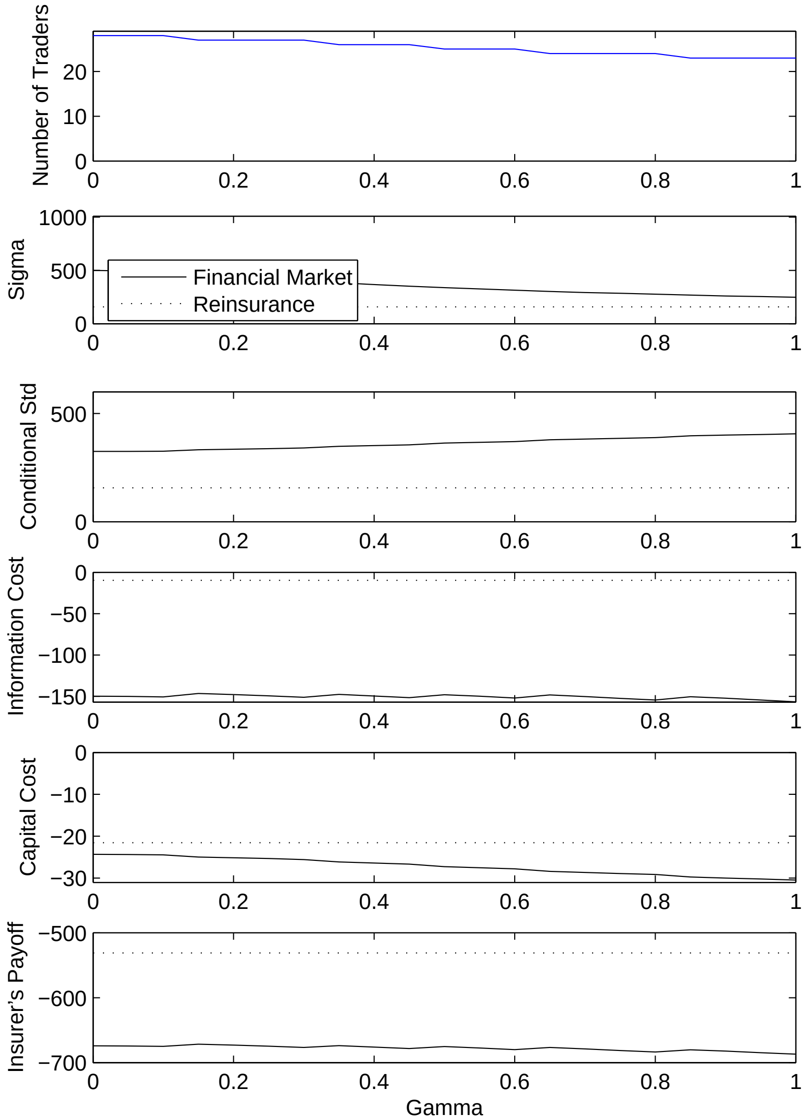

Figure 3: Solution of the model as a function of the degree of information redundancy γ with $c = 0.12$.

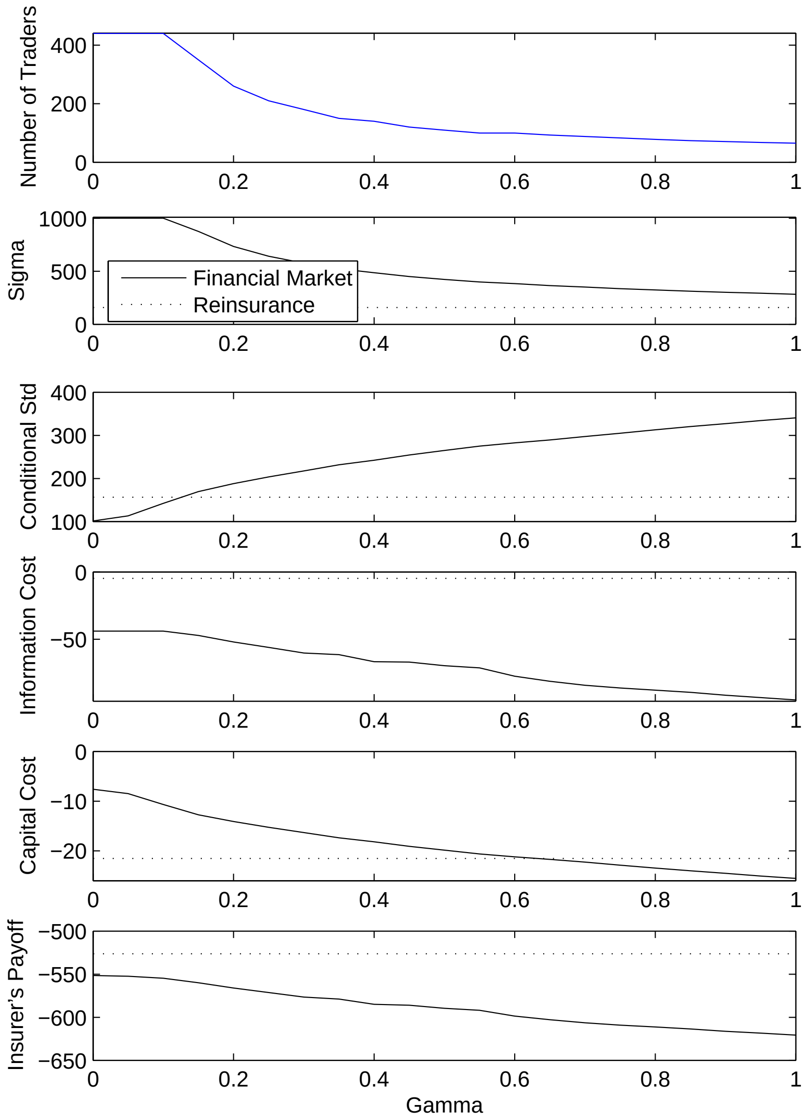

Figure 4: Solution of the model as a function of the degree of information redundancy γ with $c = 0.12$ and $k = 0.1$.

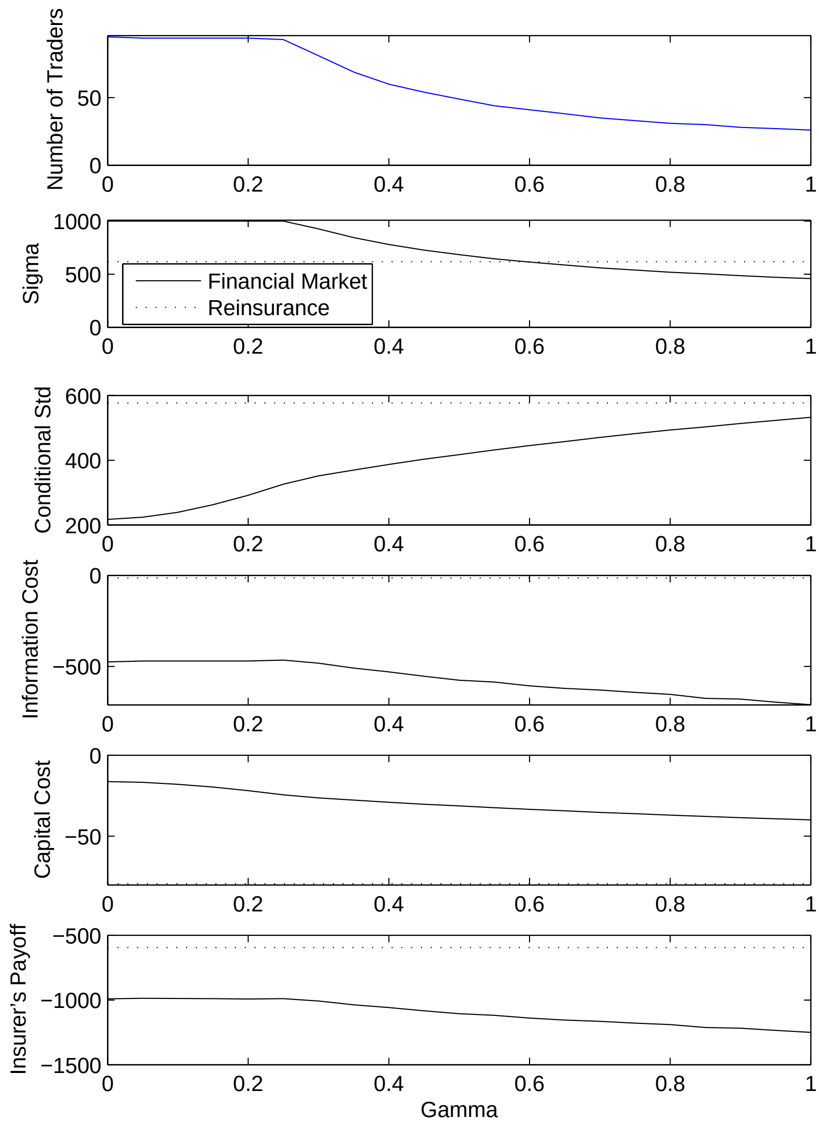

Figure 5: Solution of the model as a function of the degree of information redundancy γ with $\sqrt{v_z} = 5$.

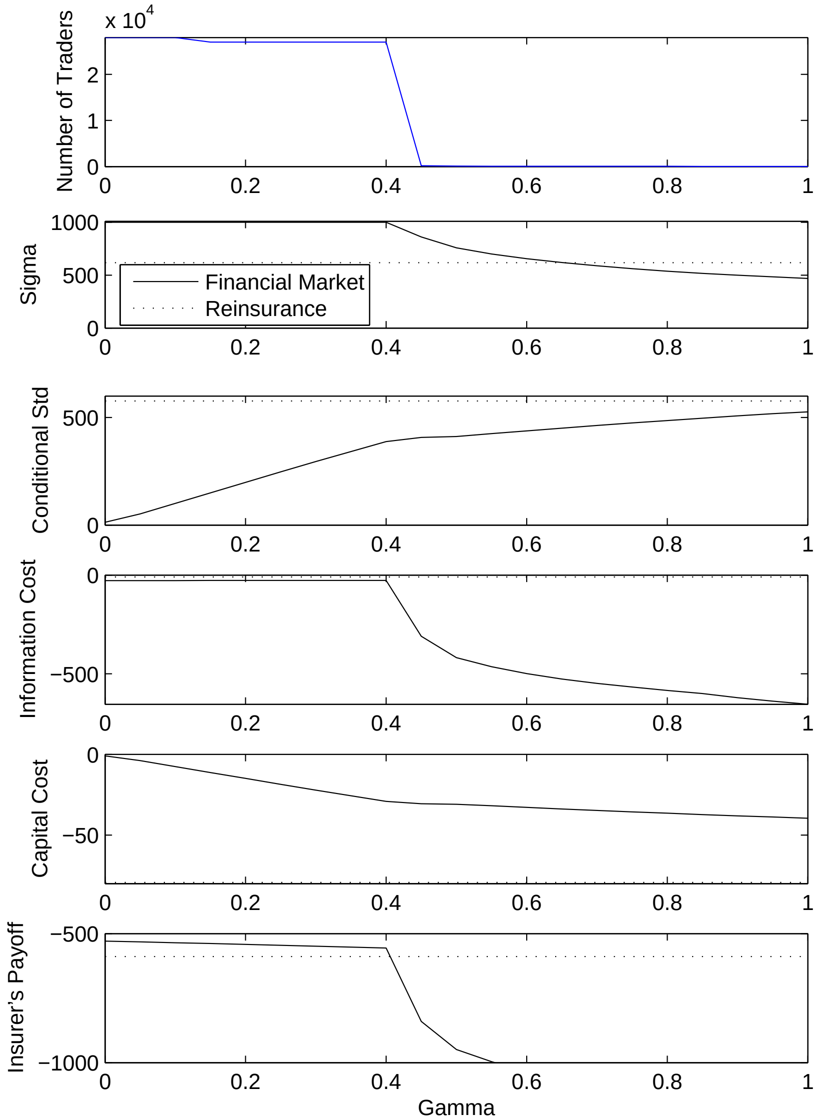

Figure 6: Solution of the model as a function of the degree of information redundancy γ with $\sqrt{v_z} = 5$ and $k = 0.001m$.

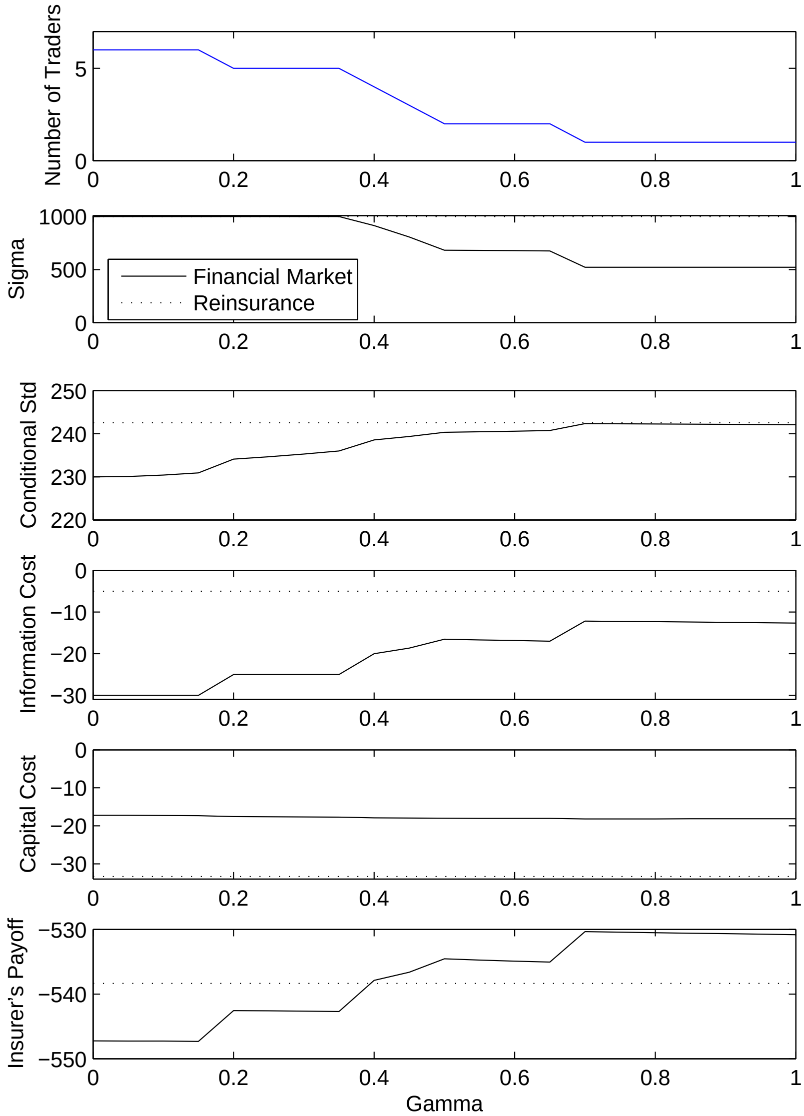

Figure 7: Solution of the model as a function of the degree of information redundancy γ with $\sqrt{v_\delta} = 250$.

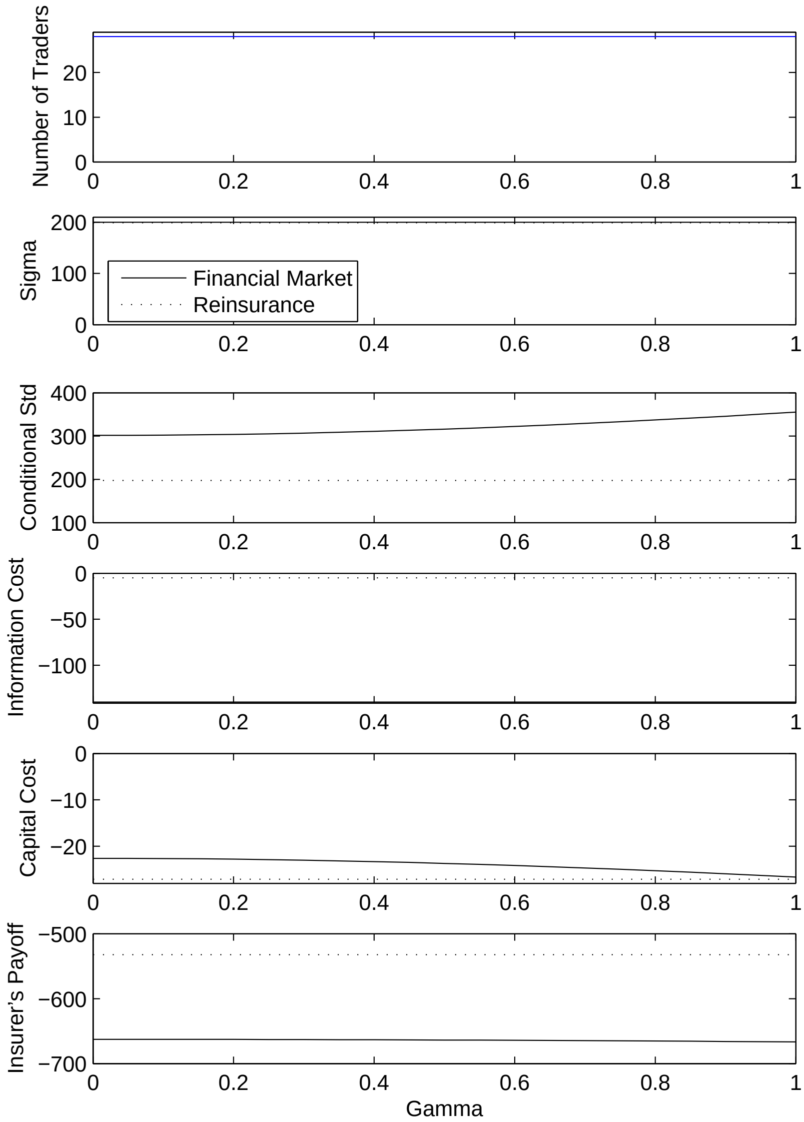

Figure 8: Solution of the model as a function of the degree of information redundancy γ with $\sqrt{\overline{v}} = 200$.

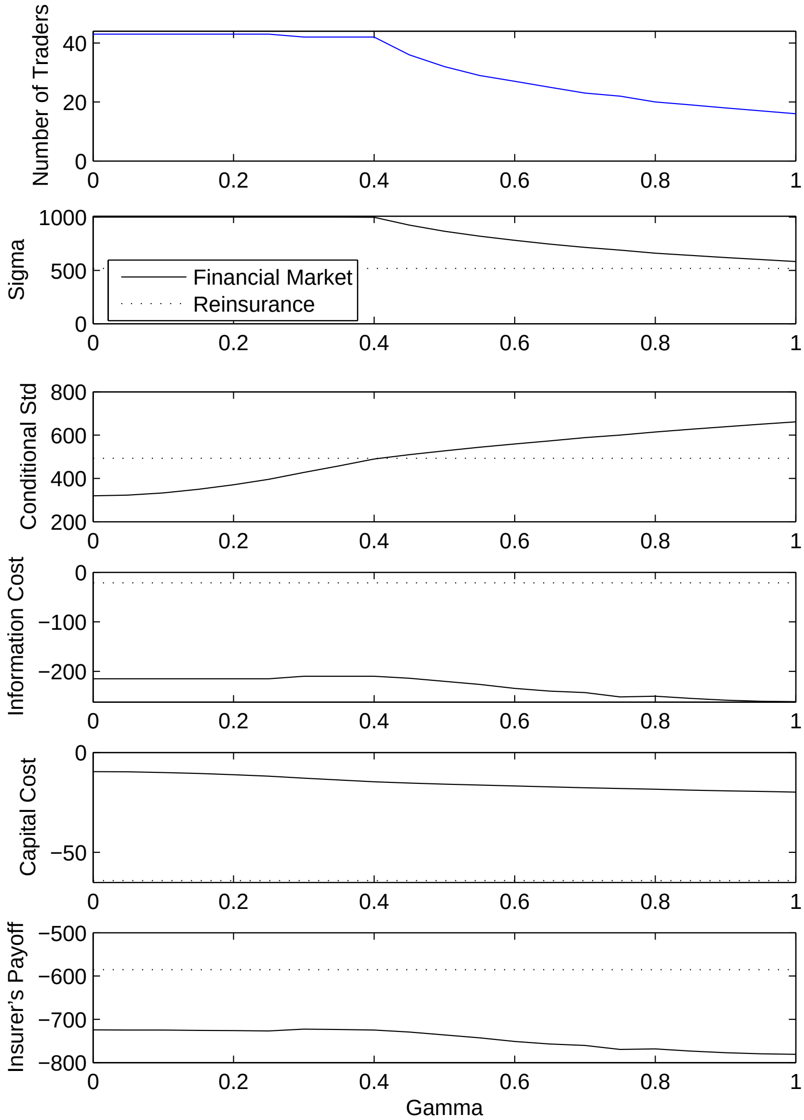

Figure 9: Solution of the model as a function of the degree of information redundancy γ with $\overline{\tau} = 0.8$.

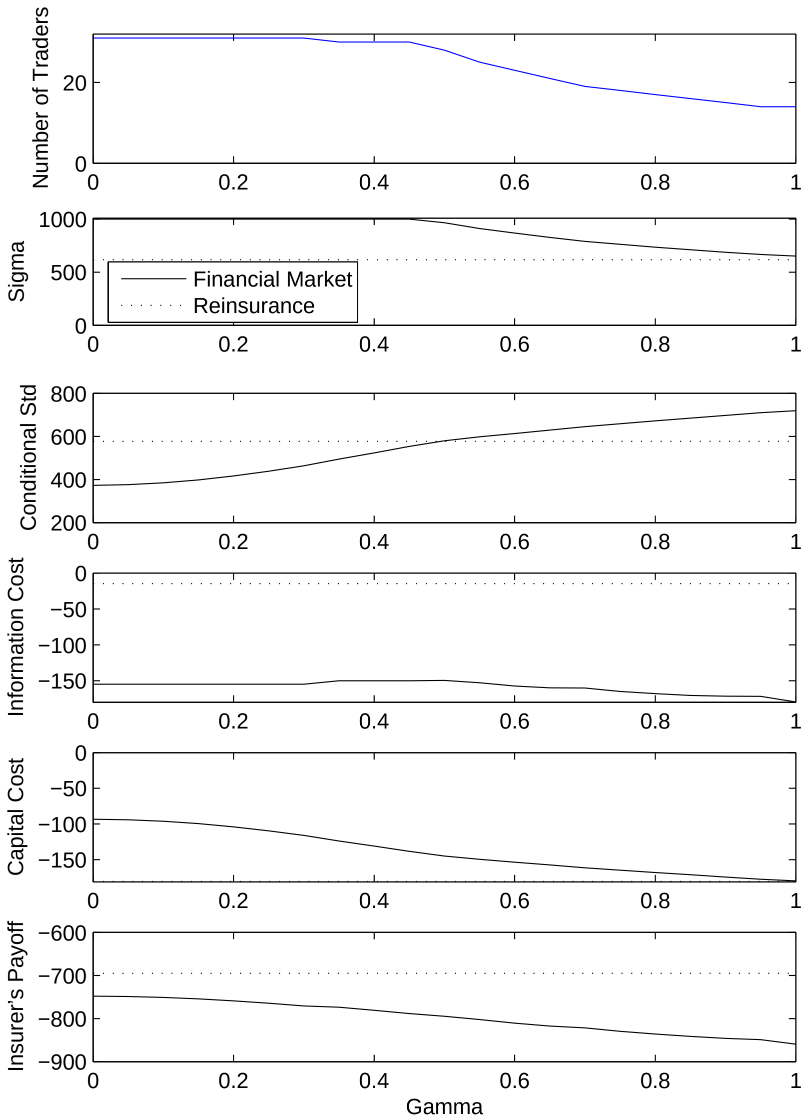

Figure 10: Solution of the model as a function of the degree of information redundancy γ with $a_i = 0.2$.

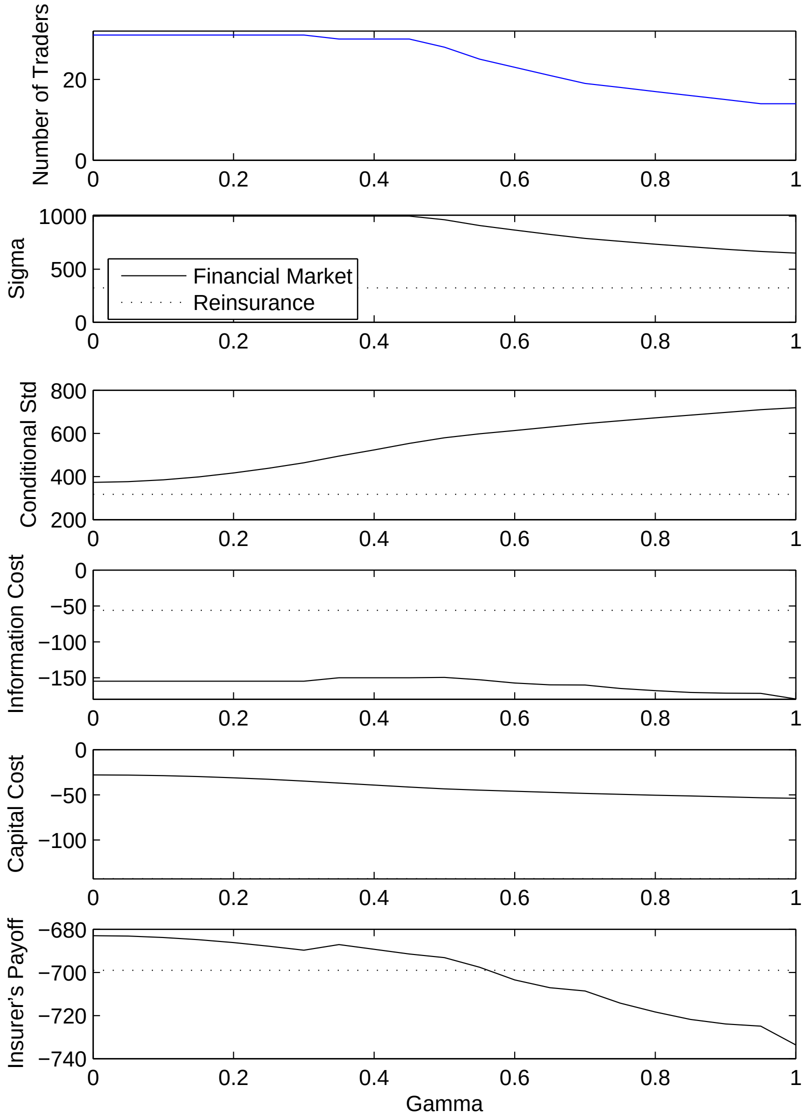

Figure 11: Solution of the model as a function of the degree of information redundancy γ with $a_r = 0.3$.

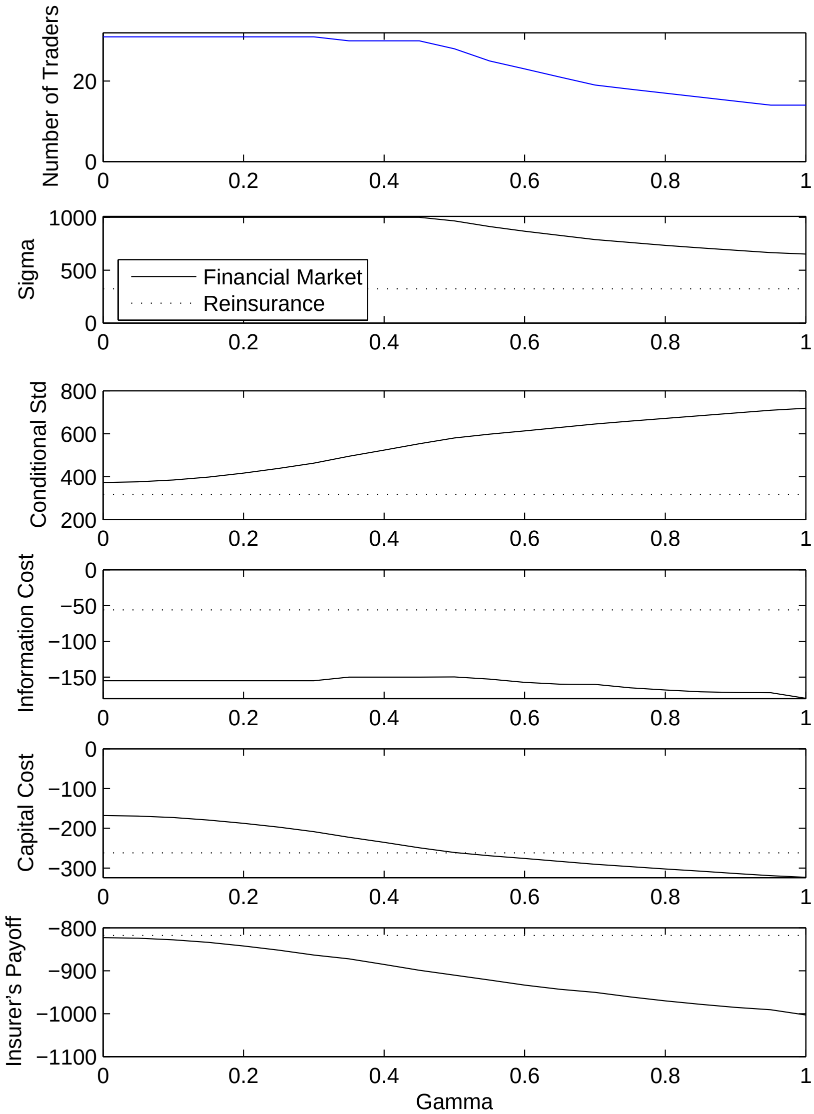

Figure 12: Solution of the model as a function of the degree of information redundancy γ with $a_i = 0.35$ and $a_r = 0.3$.