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Information Aggregation in a Catastrophe Futures Market

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We experimentally examine a reinsurance market in which participants have differing information regarding the probability distribution over losses. The key question is whether the market equilibrium reflects traders maximizing value with respect to their different priors, or whether the equilibrium is one based on a common belief incorporating all participants' information. When assuming subjects are expected value maximizers, we reject both full information aggregation and no information aggregation equilibria. We discover, as in past individual choice insurance experiments, that buyers under-assess the probabilities of large loss states, or alternatively, subjects assign larger utility values to losses than to comparable gains. After accounting for these decision theoretic concerns, the non-aggregation of information hypothesis explains the data better than full information aggregation.

INTRODUCTION

It is commonly thought that insurance markets facilitate the efficient sharing of risk, but whether they facilitate the efficient sharing of information is an open question. A defining feature of an insurance market is its underlying uncertainty. It is reasonable to assume that market participants possess differing information regarding the objective probabilities governing states of nature. When these agents participate in a market there are two natural conjectures regarding the nature of the arising competitive equilibrium. First, agents maximize their objectives (holding their priors constant) and the resulting market prices and allocations reflect efficiency with respect to these initial beliefs. Second, market prices and allocations arise that reflect a competitive outcome of agents maximizing their objectives conditional upon a common belief formed by the pooling of the agents' differing information. In the first conjecture, the invisible hand only optimally coordinates activity treating the initial beliefs as exogenous parameters, while in the second conjecture the invisible hand does substantially more. The process of market feedback aggregates disparate information and generates individually optimal outcomes with respect to the most informed sets of beliefs possible. Such a feature is highly desirable within an insurance market.

The study of whether markets efficiently aggregate information is well suited for an experimental approach. A laboratory experiment allows for the control of preferences, endowments, and information structures that are essential in identifying when a market achieves a non-information aggregation (NA) equilibrium or a full information aggregation (FA) equilibrium. Several past experimental studies have addressed this question in the context of basic asset markets with mixed results.

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Plott and Sunder (1988) find aggregation can occur when market participants have a complete set of Arrow-Debreu securities to trade, or when there are homogeneous preferences. In Forsythe and Lundholm (1990) information aggregation occurs only when traders have experience with market institutions and common knowledge of each others' dividends. Plott *et al*. (2003) find some success for information aggregation in parimutuel markets for situations for which Bayes' Law is not needed.

Unfortunately, these experiments' designs and results do not lend sufficient insight into how effectively information aggregates in an insurance market because of the strikingly different information structure. In this study we consider a property reinsurance market. It is natural to suppose a risk and information structure like that in Figure 1. Purchasers of reinsurance have considerable experience with the high-frequency, low-value claims processes represented by the left side of the figure. Sellers of reinsurance, on the other hand, with a long history of business in multiple regions and lines of reinsurance, have better information about the large less likely catastrophe risks represented by the right tail of the probability density in Figure 1.[1]

The presence of low-probability, large-loss states also is not captured in previous experimental market studies, but is an integral part of an insurance market. However, there is an extensive body of survey and experimental work addressing how *individuals* make insurance decisions when faced with low-probability, high-value risks. Slovic *et al*. (1977) and Kunreuther *et al*. (1978) find evidence of either persistent probability biases or convex utility over losses in insurance experiments. McClelland *et al*. (1993) find, when agents purchase insurance from the experimenter in a Vickrey auction, evidence of a bimodal response to very low probability risks, with some participants disregarding very small risks and others highly sensitive to small risks. None of these experiments are conducted in a bilateral-market context (i.e. subjects only perform the task of buying insurance). Also these experiments do not consider the situation of differential information.

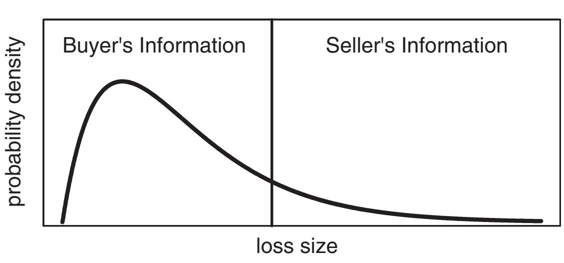

Figure 1. Reinsurance market risk and information structure.

An empirical example motivates us to draw distinct elements from the two literatures: a recent innovation in the US market for catastrophe reinsurance. After three recent low probability large loss events, Hurricane Hugo ($4.2 billion in insured claims), Hurricane Andrew (claims over $16 billion), and the Northridge Earthquake (claims over $12.5 billion), many insurers tried to withdraw from the catastrophe insurance market for earthquake risk in California and wind risk in Florida.[2] However, regulatory measures kept firms from fleeing these markets. At the same time, available reinsurance coverage grew increasingly scarce,[3] as the reinsurance market did not face the same regulations. These changes created an opportunity for new and innovative entrants to the reinsurance industry.[4] The Chicago Board of Trade (CBOT) was one of the first non-traditional entrants, inaugurating trading in Catastrophe Futures and Options in December 1992. CBOT officials were particularly enthusiastic about the potential success of catastrophe insurance futures. Numerous members of the academic community shared this enthusiasm. There were many anticipated benefits of catastrophe insurance futures and one of the strongest was the reduction of information asymmetries.[5] Despite the initial optimism, trading in the CBOT's catastrophe futures never amounted to much,[6] and they are no longer traded today. We hope our experiment sheds some light into this lack of success, and give insights into whether any market of this structure leads to information aggregation.

The results of our experiments do not offer much hope in this regard. First, when we assume individuals are expected value maximizers, the market price and quantity data do not support either an NA equilibrium or an FA equilibrium. However, there is strong evidence that prices and quantities rely more heavily upon the realization of the buyer's prior information regarding high-probability, low-loss events than the seller's prior information regarding low-probability, high-loss events. This leads us to investigate the impact that subjective probability biases and risk aversions, found in individual choice insurance experiments, could be having in our markets. We find that buyers tend to underestimate the probability of disasters while sellers on average assess these probabilities correctly. This finding is also consistent with an agent model where the correct probabilities are used by both buyers and sellers but subjects' preferences are those given in Prospect theory (Kahneman and Tversky, 1979) in which losses loom larger than gains. Once controlling for these preferences, we find that an NA equilibrium typically explains the data more robustly than does an FA equilibrium.

In the next section we present an example of a catastrophe futures market, which is also the basis of our experiment, and then we present the implications of the Full Aggregation and Non-aggregation equilibrium concepts. Then we present our experimental design. After which we present the results of our experimental markets. We conclude with some comments on the implications of our work for those who are looking to novel securities for insurance solutions.

A SIMPLE MARKET FOR CATASTROPHE FUTURES AND EQUILIBRIUM HYPOTHESIS

We now describe the demand and supply conditions of an elementary market for a catastrophe index future that we use in our experiments. Primary insurers, who purchase catastrophe futures to help reinsure the risks inherent in their portfolio of property insurance policies, determine the demand conditions. Reinsurers, who sell future contracts, determine the supply conditions. The catastrophe future pays a dividend that is proportional to an index of all claims made on the property insurance policies sold by primary insurers.

Consider a primary insurer who sells property insurance policies that generate a total fixed premium income of \$4.60. There are four different states of claim levels which we denote $\{N_L, N_H, D_L, D_H\}$—N and D are for normal and disaster states and L and H are for low and high losses. The set of insurance policies has a corresponding set of four possible levels of liabilities, {\$2, \$4, \$10, \$20}. In the absence of any other purchases or sales of securities, the primary insurer has a set of four possible net income, {\$2.60, \$0.60, −\$5.40, −\$15.40}.

We now introduce a security that trades after the primary insurer collects premiums but before the level of liabilities is determined. When the amount of liability is determined, the dividends on the introduced security are paid. Now let us assume there are a total of six such primary insurers and, for simplicity, further assume that their liabilities are perfectly correlated. An index of these insurers' liabilities has four possible values {\$12, \$24, \$60, \$120}. Define a future contract on this index such that seller of the contract pays the purchaser a dividend one-twelfth of the realized value of liability index, or the future contract has four potential dividend levels {\$1, \$2, \$5, \$10}. Notice if a primary insurer purchases two such future contracts he is fully insured and will have a net income of \$4.60 less the price paid for the two contracts regardless of the state. When the expected net income position is the sole consideration, the maximum amount a risk neutral primary insurer is willing to pay for a unit of the security is the expected dividend.

The reality of the property insurance market dictates that value of assets providing reinsurance to primary insurers rely upon more than just the expected dividend. For example, the property insurance market is highly regulated, and regulatory bodies closely monitor and restrict risk position of insurers' portfolios of policies and securities.[7] To capture the impact of regulatory mandates and incentives to hold conservative financial positions we specify that a primary insurer derives additional value from the purchase of future contracts that is independent of the realized dividend. Specifically we denote the marginal amount of this additional valuation for the first four contracts purchased—as we will restrict the maximum number of contracts purchased to four—is (\$0.54, \$0.30, −\$0.34, −\$0.58). Notice that this schedule provides a positive reward for the purchase of contracts that lead to a more fully insured portfolio, and a negative reward for contracts that lead an over-insured and more risky portfolio. The magnitude of the rewards is increasing in the distance one's portfolio is from the fully insured position.

A primary insurer's state dependent demand functions for each of the four possible liability outcomes is simply the sum of the reward schedule that is independent of the state and the dividend received in the state. This family of state dependent demand functions is presented in Figure 2.

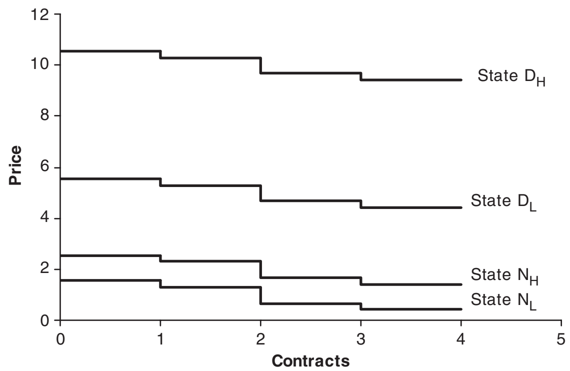

Figure 2. A primary insurer's state dependent demand functions for future contracts.

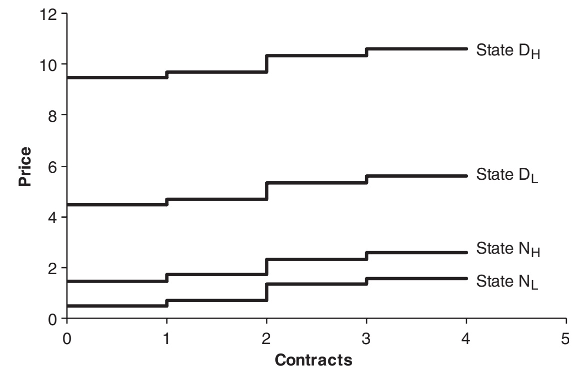

Figure 3. A reinsurer's state dependent supply functions for future contracts.

Notice that family of demand functions differ by their *y*-axis intercepts. This is due to the fact that vertical location of the demand curve is determined by the state dividend. Consequently, a primary insurer's *expected* demand curve is defined by the expectation of the intercept value, or in other words the expected dividend. Furthermore, a change in the expected value of the dividend leads to a vertical shift of the demand curve. Finally, the market expected demand curve is found by a horizontal summation of the individual expected demand curves.

The sellers in this catastrophe futures market are large reinsurers who do not hold any retail property insurance policies. In our experiments we will have six such sellers. The revenue received from the sale of future contracts is the sole source of value for a reinsurer in this market. There are two sources of cost for selling contracts. First, the dividend that reinsurer must pay on each contract sold is the state dependent marginal cost for a contract. Second, reinsurers are also subject to regulatory mandates and incentives on their portfolios like primary insurers. For example, a local regulator can penalize a reinsurer for not providing a certain amount of coverage in a market. We summarize the costs resulting from the effects as the state *independent* marginal cost schedule, (−\$0.54, −\$0.30, \$0.34, \$0.58). The negative values correspond to avoiding the regulatory cost of not providing enough liquidity to the market, and the positive costs are associated with excess volatility in the portfolio.

A reinsurer's state dependent supply functions for each of the four possible liability outcomes is simply the sum of the marginal cost schedule that is independent of the state and the dividend paid in the state. The state dependent supply curves are present in Figure 3, and like the demand case, only differ by their *y*-axis intercepts as determined by the state dividend. Thus the vertical placement of a primary insurer's *expected* supply curve is defined by the expected dividend value and any change in the expected value of the dividend leads to a vertical shift of the expected supply curve. Finally, the market expected supply curve is found by a horizontal summation of the expected individual supply curves.

Clearly, the equilibrium prices and quantity of contracts will depend upon the probabilities that buyers and sellers place on the four possible loss states. As we described in the introduction, there are strong reasons to believe that buyers have better information regarding high probability small loss states of the world while sellers have better information regarding low probability large loss states of the world. We now present a simple way to operationalize this notion. Recall we have four possible states of the world, $\{N_L, N_H, D_L, D_H\}$ corresponding to the primary insurer's possible liabilities {\$2, \$4, \$10, \$20}. Now Let {0.45, 0.45, 0.05, 0.05} be the prior probabilities over these possible losses. Before the market for future contracts, buyers receive information that allows them rule out the high (H) or low (L) loss conditional upon a normal state (*N*) occurring. Likewise, sellers receive information that allows them rule out the high (H) or low (L) loss conditional upon a Disaster state (*N*) occurring. This process generates in four distinct *prior information regimes*, which we denote LL, LH, HL, HH. The first letter in a pair refers to the

Table 1. Prior Information Regimes

Regime	Buyer prior	Seller prior	Aggregate
(LL)	(0.9, 0, 0.05, 0.05)	(0.45, 0.45, 0.1, 0)	(0.9, 0, 0.1, 0)
(LH)	(0.9, 0, 0.05, 0.05)	(0.45, 0.45, 0, 0.1)	(0.9, 0, 0, 0.1)
(HL)	(0, 0.9, 0.05, 0.05)	(0.45, 0.45, 0.1, 0)	(0, 0.9, 0.1, 0)
(HH)	(0, 0.9, 0.05, 0.05)	(0.45, 0.45, 0, 0.1)	(0, 0.9, 0, 0.1)

remaining Normal state and the second letter refers to the remaining Disaster state. Table 1 gives the priors the buyers and sellers, respectively, hold at the start of the futures market. Of course our question of interest is whether the competitive forces of the market will leads to aggregation of this disparate information. The final column of Table 1 presents the prior distribution that results when the buyers' and sellers' information is aggregated.

Using the information in Table 1, we can fully specify the market demand and supply curves are depending upon the disparate priors and aggregate priors. The hypotheses of interest are full information aggregation (FA) versus non-information aggregation (NA). The basis of the FA hypothesis is the ability of a market to generate an information aggregation equilibrium, i.e. the market generates a competitive outcome that reflects the pooling of all diverse information regarding the true state of nature. The competitive equilibrium prices and allocations that arise under FA hypothesis are those generated by expected demand and supply curves which use the aggregate prior to calculate the expected dividend. The NA hypothesis is generated by the conjecture that the market generates a competitive outcome reflecting the agents' prior beliefs regarding the true state of nature. The competitive equilibrium prices and allocations that arise under NA hypothesis are those generated by expected demand and supply curves which use the respective priors to calculate the expected dividend.

The impact of these two competing models is generated through differing expected dividend values. Under the FA conjecture, a competitive outcome reflects a common expected dividend value based on the pooling of buyers' and sellers' private information. The expected value is calculated as

$$E[d(s)] = 0.9\ (\text{remaining } N\text{-state's dividend}) + 0.1\ (\text{remaining } D\text{-state's dividend}). \quad (1)$$

On the other hand, if the NA conjecture holds true, the market outcome will reflect the following distinct expected dividends for the buyer and seller;

$$E[d(s)]_{\text{buyer}} = 0.9\ (\text{remaining } N\text{-state's dividend}) + 0.1\ (\text{average } D\text{-state's dividend}) \quad (2)$$

and

$$E[d(s)]_{\text{seller}} = 0.9\ (\text{average } N\text{-state's dividend}) + 0.1\ (\text{remaining } D\text{-state's dividend}). \quad (3)$$

Buyers' and Sellers' expectations of the dividend values determine the vertical location of supply and demand curves. Hence, the implications of the comparative statics of FA versus NA are obtained from the inspection of the competitive equilibrium for their respective supply and demand curves. Table 2, and Figures 4 and 5 summarize the equilibria for the two models in the four prior information regimes.

Figure 4 shows the market supply and demand curves under the FA premise for the four prior information regimes. First, notice that for all four prior information regimes the equilibrium market quantity is twelve units. In other words, buyers fully reinsuring their endowed portfolio risk. Turning our attention to price, the FA outcome generates distinct equilibrium price tunnels. The midpoints of these price tunnels represent actuarial fair premiums for reinsurance.

In any prior information regime, the NA model will distinctly differ from the FA model in either the equilibrium price or quantity. In the LH and HL regimes, the NA and FA models only differ strongly in equilibrium quantities. The NA model predicts that in the LH regime only 6 units are traded, resulting in an under-provision of reinsurance; in the regime HL 18 units are traded, and there is an over-provision of reinsurance. One can also observe that under prior information regimes LL and HH the equilibrium prices are distinct under the FA and NA hypotheses, but full

Table 2. Model Predictions for Equilibrium Prices and Quantities

			Disaster state Low LL	High LH
Normal state	Low	FA model: NA model:	12 units, \$1.30–\$1.50 12 units, \$1.75	12 units, \$1.80–\$2.00 6 units, \$1.81–\$2.19
			HL	HH
	High	FA model: NA model:	12 units, \$2.20–\$2.40 18 units, \$2.19–\$2.21	12 units, \$2.70–\$2.90 12 units, \$2.25–\$2.65

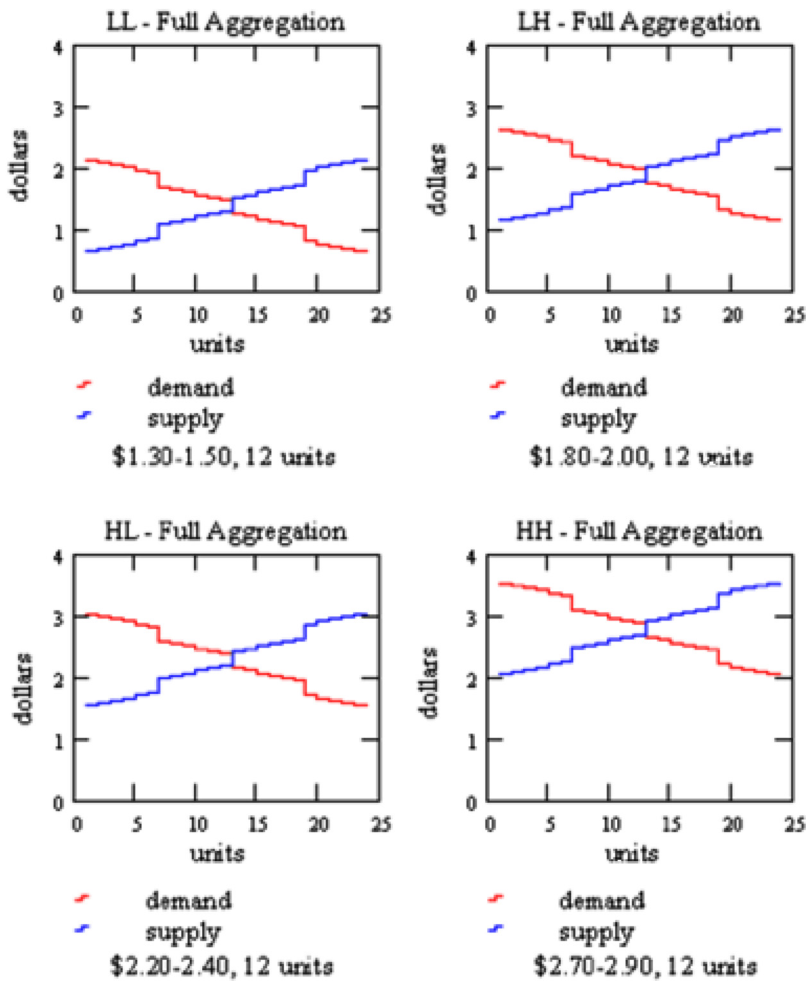

Figure 4. Full-aggregation equilibrium induced supply and demand.

reinsurance is achieved in both scenarios. However, in these two regimes the NA hypothesis does not generate actuarial fair reinsurance premiums: In HH, the midpoint of the price tunnel is below the actuarial fair rate and in LL the midpoint is above the actuarial fair rate.

EXPERIMENTAL DESIGN

In our experiments, twelve participants are randomly partitioned into groups of six Buyers and six Sellers. An experiment consists of a series of trading periods. In each period, Buyers and Sellers

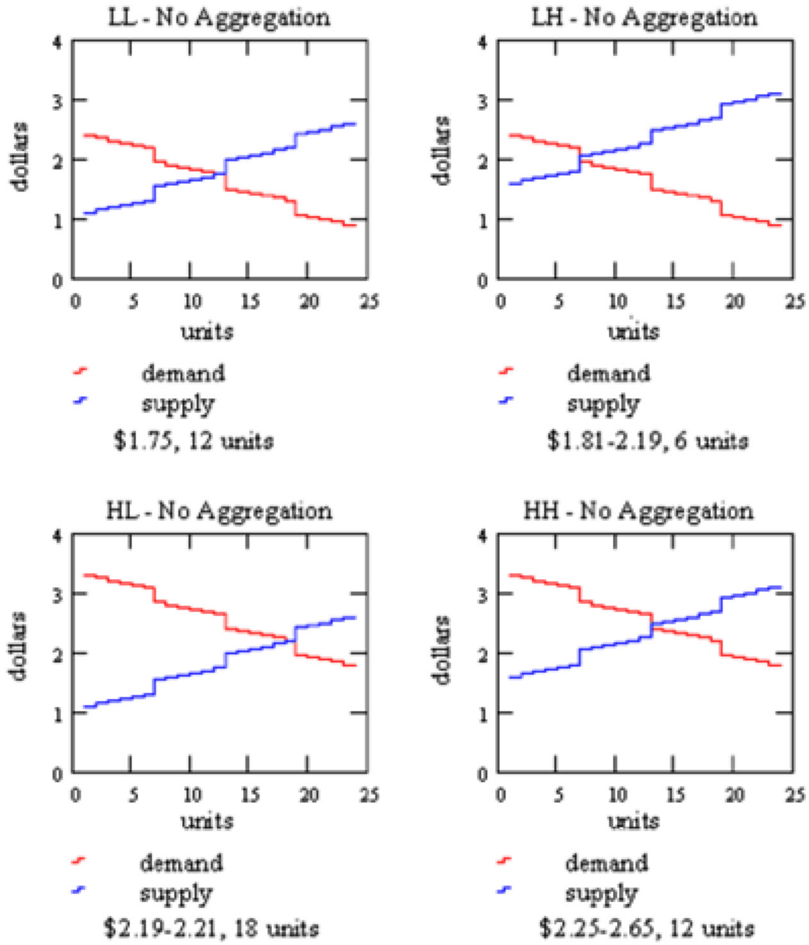

Figure 5. No-aggregation equilibrium induced supply and demand.

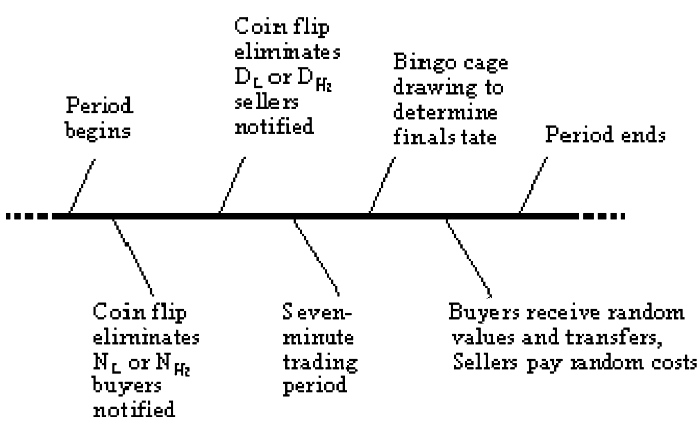

Figure 6. Time Line for a trading period.

have the opportunity to trade an asset in an oral double auction. Before the auction starts, Buyers and Sellers are privately given information relevant to the distribution of the dividend. After the auction, the experimenter conducts a probability experiment that determines the actual dividend for the trading period.

Consider the time line in Figure 6. Before the start of each trading period, the experimenter flips a coin. If the result is heads, the N_L state is eliminated. If the result is tails, the N_H state is eliminated. Buyers are privately informed of the remaining Normal state (N_L or N_H) with the use of a code sheet. Likewise, a second coin toss is used to eliminate one of the Disaster states. Sellers are privately informed of the remaining Disaster state (D_L or D_H).

Next a seven-minute open outcry double auction commences. Buyers may offer bids or accept asks, and sellers may make asks or accept bids in an oral double auction format. A valid bid or ask must improve upon any standing bid or ask. Once a bid or ask is accepted, bidding starts over; buyers are then free to open bidding at any non-negative price, and sellers are free to make an initial ask at any price between \$0 and \$20. Bids, asks, and trades are displayed on an overhead projector as they are made. After the seven-minute trading period has expired, the final state of nature is resolved by drawing one ball from the bingo cage in view of the participants. If the ball is numbered '1' through '9', the result is the remaining Normal state. If a '10' is drawn, the result is the remaining Disaster state. The ball is returned to the bingo cage prior to the next trading period. Buyers then receive the random values of the units they purchased and the random transfers (the net premium income or premium less the realized liability), and sellers pay the random costs of the units they sold.

Figure 7 below is a typical Buyer's Decision Sheet. In row number 1 Buyer 1 carries over cumulative earnings from the previous period (\$0.00 since this is the first period). On the left side of the Buyer's Decision sheet are four columns labeled $X1$, $X2$, $Y1$, and $Y2$, corresponding to the state-space (N_L, N_H, D_L, D_H). In this period the statement 'not White' would inform Buyers that $X1$ had been eliminated, and 'not Blue' that $X2$ had been eliminated. There are no codes listed for the 'Y' states (D_L, D_H), since the buyers are not privy to this information. The values in row number 2 are net premiums which apply in each state. Similarly, in rows three, six, nine and twelve the values for each of the four units that Buyer number 1 may purchase are listed for each of the four states. For each unit he purchases, Buyer 1 enters the purchase price in the appropriate space on the far right column. After trading is finished the final state is drawn and then completes the decision sheet. Figure 8 presents a typical Seller's decision sheet.

Market participants are inexperienced prior to their arrival for the experiment. The subjects first privately read written sets of buyer or seller instructions on the Double Auction procedures. Next subjects privately read instructions on how the two coins tosses and the draw from the Bingo cage determined the state. Then these common instructions were read out loud by the experimenter as well and the experimenter conducted the natural probability experiment twice without trading. Finally subjects participated in one to three practice periods that include trading in the security.[8]

Buyers and Sellers begin the experiment with zero cash endowments. They are permitted to run negative cash balances without being expelled from the experiment, but receive no compensation other than a non-salient show-up fee of five dollars if their cumulative earnings are negative at the end of the experiment. Subjects were informed of this limited liability. Unfortunately, this came into play in one of our sessions there was two disasters and in which three sellers ended with negative balances. The number of periods over nine is randomly determined, and participants are not informed ahead of time which period will be the final period.

RESULTS AND ANALYSIS

We focus our analysis of the experimental data into two activities. First, we compare how well the data conforms to our interior predictions for price and quantity for the two competing models. Prices and quantities for units traded each period, with few exceptions; do not match the equilibrium predictions for either the full-aggregation or the no-aggregation model. Prices typically are lower than either model's predictions and market prices do not depend on the sellers' prior information. The volume of reinsurance contracts also does not reflect either model's predictions. We do observe that the impact of buyers' prior information is more influential on quantity than is the sellers' prior information.

Since prices are generally lower than either hypothesis predicts, and buyers' prior information has a greater than expected impact on both price and quantity, we consider alternative explanations. We turn to the experimental and survey research on disaster insurance for possible explanations. Given the subjective probability biases

Buyer Decision Sheet for Buyer # 1 Period: 1

Name: ____________________

Probability of an X-state: 90%

Probability of a Y-state: 10%

State				Unit #	Row #		
X1 White	X2 Blue	Y1 —	Y2 —		1	Cumulative Earnings	0.00
2.60	0.60	-5.40	-15.40		2	Random Transfer	
1.54	2.54	5.54	10.54	1	3	Unit Value	
					4	Purchasing Price	
					5	Unit Earnings (3 - 4)	
1.30	2.30	5.30	10.30	2	6	Unit Value	
					7	Purchasing Price	
					8	Unit Earnings (6 - 7)	
0.66	1.66	4.66	9.66	3	9	Unit Value	
					10	Purchasing Price	
					11	Unit Earnings (9 - 10)	
0.42	1.42	4.42	9.42	4	12	Unit Value	
					13	Purchasing Price	
					14	Unit Earnings (12 - 13)	
					15	Total Unit Earning s (5+8+11+14)	
					16	Period Net Earning s (2 + 15)	
					17	Cumulative Earnings (1 + 16)	

Figure 7. A buyer's decision sheet.

that underestimate the probability of disaster states found in these literatures, we explore the possibility that the buyers' and sellers' possess this bias in our experiment. From the experimental market data, we calculate implicit subjective probability beliefs of a disaster for both buyers and sellers under the FA and NA hypotheses. The result of this exercise suggests there is a strong bias: the buyers' implicit beliefs are typically below the sellers' implicit beliefs (which are on average statistically indistinguishable from 10%). Once we account for this bias, there is evidence that the NA assumption is more appropriate. We also point out that there is an alternative to our subjective probability bias conclusion: individuals use the objective probabilities but differ in the way they evaluate risky choice. In this scenario we conclude that the implications of prospect theory hold: sellers' losses loom larger than buyers' gains.

Data Preliminaries

We start by presenting the data from the five catastrophe futures markets in Figures 9–13. We

Seller Decision Sheet for Seller # [1] Period: [1]

Name: ____________________

Probability of an X-state: 90%

Probability of an Y-state: 10%

State				Unit #	Row #		
X1	X2	Y1	Y2		1	Cumulative Earnings	0.00
—	—	Mango	Grape				
					2	Selling Price	
0.46	1.46	4.46	9.46	1	3	Unit Cost	
					4	Unit Earnings (2 - 3)	
					5	Selling Price	
0.70	1.70	4.70	9.70	2	6	Unit Cost	
					7	Unit Earnings (5 - 6)	
					8	Selling Price	
1.34	2.34	5.34	10.34	3	9	Unit Cost	
					10	Unit Earning s (8 - 9)	
					11	Selling Price	
1.58	2.58	5.58	10.58	4	12	Unit Cost	
					13	Unit Earnings (11 - 12)	
					14	Total Unit Earnings (4+7+10+13)	
					15	Cumulative Earnings	

Figure 8. A seller's decision sheet.

show the transaction prices for each experiment in chronological order, separated by trading period. For each period, the shaded areas represent the quantities and the range of prices we would expect to observe if markets are in the FA model equilibrium. The NA model equilibrium prices and quantities are the clear areas; overlapping regions are cross-hatched. The x-axis gives the period, prior information regime, and the triple FA predicted quantity/NA predicted quantity/observed quantity.

For example, in the first period of Experiment 1 in Figure 2.10, the information set is LL. The no-aggregation model prediction of 12 units traded at $1.75 is represented as a horizontal line 12 units wide. The full-aggregation model prediction—12 units traded between $1.30 and $1.50—is represented by the shaded area. The line representing actual trades shows the first unit traded at $2.25. Subsequent prices fell rapidly to the full-aggregation price range, and the total quantity traded was 9 units.

Price and Quantity Data Analysis

A visual inspection of Figures 10–14 quickly reveals that the observed prices tend to lie outside the ranges predicted by either model. To

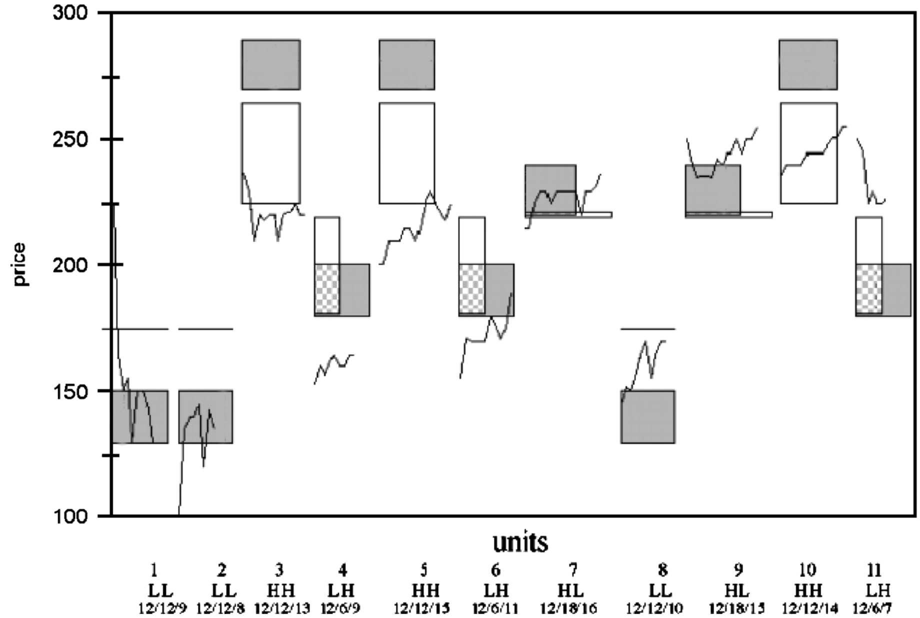

Figure 9. Market 1.

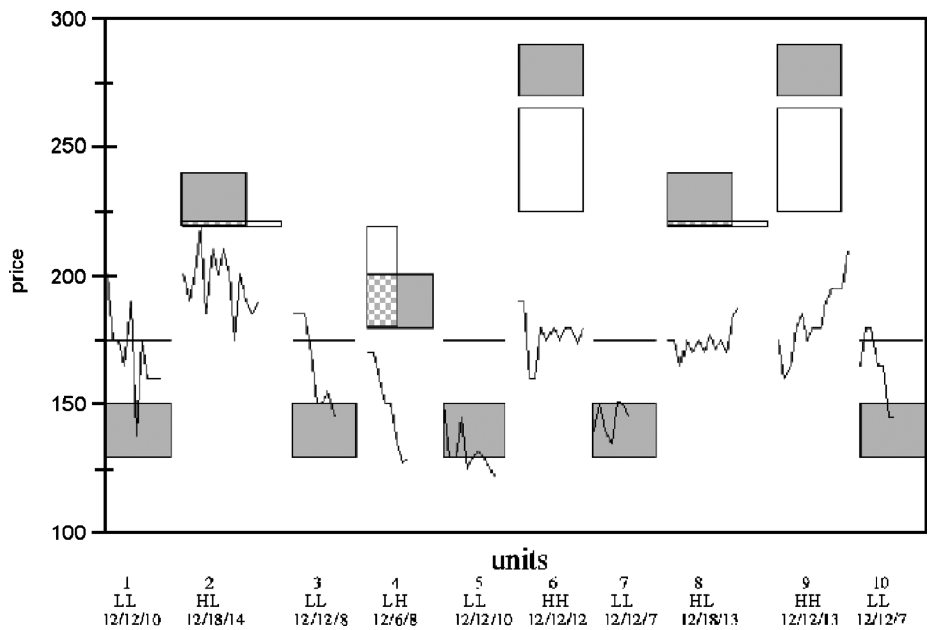

Figure 10. Market 2.

assess the impact prior information has on prices we obtain the ordinary least squares estimate of the coefficients in the following dummy variable equation:

$$\text{Price} = \alpha_1 \text{LL} + \alpha_2 \text{LH} + \alpha_3 \text{HL} + \alpha_4 \text{HH}$$

The results of this regression, along with NA and FA price predictions, are given in Table 3. First notice that mean price for each prior information regime falls below the predicted range except in the case of the FA prediction in the LL regime. The second striking result is that price seems to solely depend upon the buyer's prior information. Specifically, the mean prices in LL and LH are close and the mean prices in HL and HH are close. We conduct an *F*-test to confirm

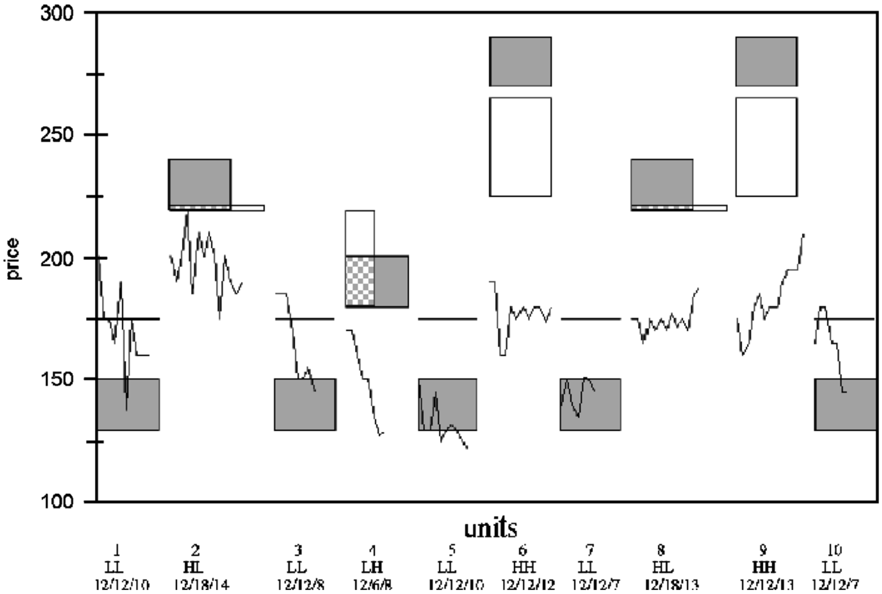

Figure 11. Market 3.

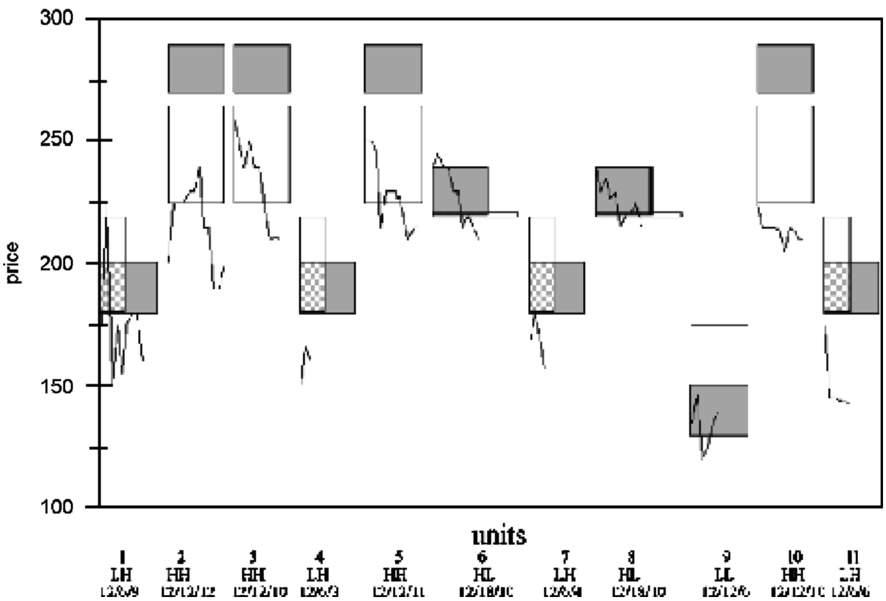

Figure 12. Market 4.

this observation. The *F*-statistic for the hypothesis that $\alpha_1 = \alpha_2$ and $\alpha_3 = \alpha_4$ is 2.63 with a *p*-value of 0.073.

These results regarding price are quite surprising given the results of similar treatments in Plott and Sunder (1988). In three of their experimental sessions, subjects are given homogeneous preferences over dividends, thus giving an ordinal ranking of states. Strong convergence to the FA predicted prices occurred by the end of each of the three sessions.[9] The lack of price convergence in our experiment must result from one or some combination of the following: correlation of prior information with buyer and seller roles, pooled information does not reveal the true state of nature, the low probability of large loss states, and how individuals form assessments in the presence of this uncertainty.

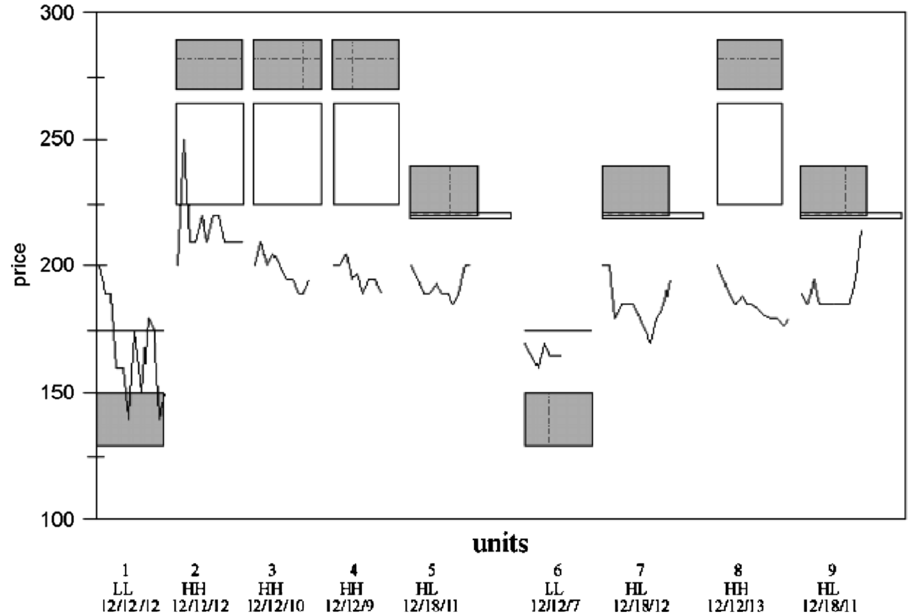

Figure 13. Market 5.

Before completely dismissing the applicability of either model, consider the effects a probability bias might have on the hypothesized prices. The price data imply that market participants may tend to under-weight the probability of a disaster state occurring. Note that under the FA model we would expect the difference in price between low and high normal-state information sets to average 90¢, and under the NA model, 45¢. As the probability of a disaster state goes to zero, these predictions approach \$1.00 and 50¢, respectively. The difference we observe—about 53¢—is supportive of the NA hypothesis. We more vigorously pursue this idea below.

One of the attractive features of our induced supply approach is the ability to discriminate between models through the inspection of quantities. In the five futures markets, observed quantities tend to diverge from those predicted by either model. The lack of convergence in quantity is readily seen in the Figures 9–13. We now ask whether either model can explain the average market quantities. Recalling the quantity predictions of the two models summarized in Table 2, note that under the FA model we expect 12 units to be traded in each period. Also note that under the NA model the quantity prediction differs in two prior information regimes: in LH the quantity is six and in HL the quantity is eighteen. The FA and NA models both give testable implications in the following expression:

$$Q_t = \alpha + vHx_t + \delta xH_t,$$

where Q_t is the market quantity in period t, Hx_t is dummy variable for the prior information regimes in which buyers are informed that the low Normal state is eliminated (i.e. regimes HL and HH), and xH_t is a dummy variable for the prior information regimes in which the seller has been informed that the low Disaster state is eliminated (i.e. LH and HH). Under the FA model, $\alpha = 12$ and $v = \delta = 0$ and under the NA model $\alpha = 12$ and $v = -\delta = 6$. The OLS estimates of these coefficients are presented in Table 4. The F-statistic for this regression (24.301) rejects the hypothesis that the mean quantity is independent of the prior information regime. This is a rejection of the FA coupled with symmetric subjective probability beliefs of a Disaster state. On the other hand, the estimated model coefficients do not follow the predictions of the NA model either. The estimated value of α (9.0) is not the predicted 12 units, and a t-test indicates a 0.00 probability that $\alpha = 12$. While the estimated values of v and δ are significantly different from zero, and have the correct sign for the NA model, they are not equal to 6 and -6, respectively. The probability that v, given an estimated value of 4.7, is equal to 6 is 0.059 and the probability that δ, given an estimated value of -1.5, is equal to -6 is 0.000,

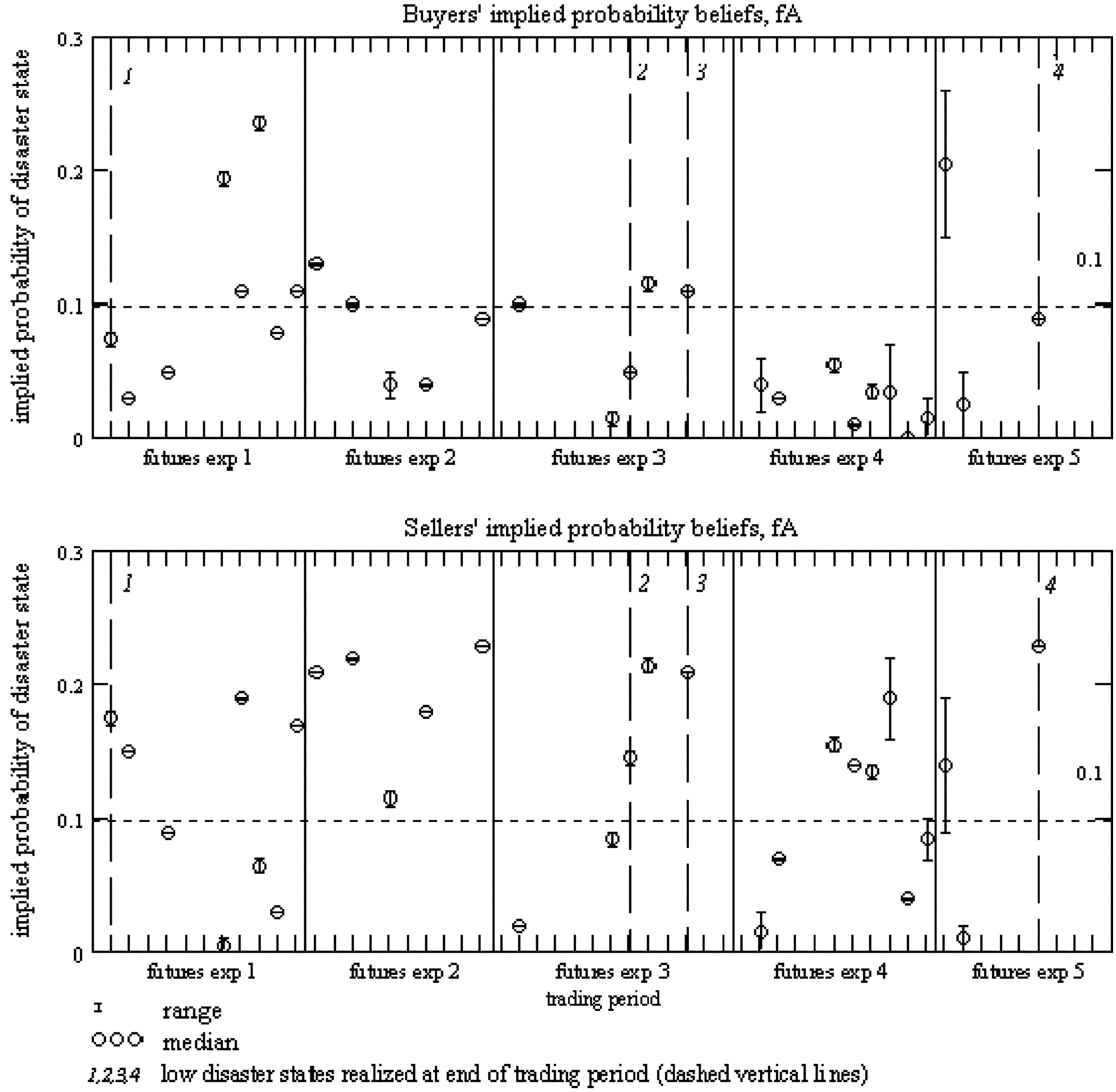

Figure 14. Buyer's and seller's implied probability beliefs under full-aggregation model.

Table 3. Dummy Regression: Price $= \alpha_1$LL $+ \alpha_2$LH $+ \alpha_3$HL $+ \alpha_4$HH

Variable	Coefficient	Standard error	FA prediction	NA prediction
LL	153.28	2.189	130–150	175
LH	161.19	3.072	180–200	181–219
HL	210.35	1.828	220–240	219–221
HH	210.71	1.819	270–290	225–265

Table 4. Regression: $Q_t = \alpha + vHx_t + \delta xH_t$

Variable	Coefficient	Standard error	T-statistic
Constant	8.99	0.563	0.000
Hx	4.69	0.681	0.000
xH	−1.50	0.679	0.032

again according to two-sided t-tests. The other notable result of this exercise is the magnitude of v is significantly greater than δ. This result is indicative of the more significant impact the buyers' information has than the sellers' information.

In our analysis of prices we noted that observed biases were consistent with the buyers and sellers assigning a probability of a disaster state as less than 10%. Is this consistent with the data on quantities? If buyers and sellers tend to underweight the probability of a disaster, we would still expect under the FA model a quantity of 12 units traded in each period. Under the NA model, we would expect, as observed, a value for $|\delta|$ less than 6; as the probability of a disaster state goes to zero, δ goes to 0 as well. As the perceived probability of a disaster declines, however, the observed value of v should increase under the NA model, converging to 7 as the probability of a disaster state goes to zero, contrary to our result. How then do we account for these results? Some possible explanations for our results are that the experimental subjects' perceived probability of a disaster state changes over time, that buyers' and sellers' beliefs may differ, or both.

Subjective Probability Biases

We assess whether subjective probability biases combined with either the FA or NA model can rationalize our market data. We start by assuming that the market prices and quantities we observe each period reflect a competitive equilibrium. This assumption relies upon the oral double auction's substantial history of robustly generating competitive outcomes in induced supply and demand experiments. Next we know that the schedules of private marginal valuations and costs give us the slopes of the demand and supply curves. What is not known is the vertical location of these curves as these are defined by the experimental subjects' subjective probability beliefs of a disaster state. We further assume that all buyers have the same belief and that all sellers have the same belief. The size of a vertical shift given a belief depends upon whether there is information aggregation or not. We proceed by calculating implicit beliefs under both the FA and NA hypotheses. To summarize, we have two parameters (the subjective size of the supply and demand curves' positive vertical shifts) whose values we can use to calibrate the observed market price and quantity.

The answer to the following question is not obvious; are there role-specific probability biases which can explain our results under these two models? To address this question, we perform a numerical exercise in which we deduce the implicit probability biases for buyers and for sellers using the FA and NA hypotheses. The are four main conclusions: the NA model most plausibly explains results in most periods, buyers' average implied beliefs of disaster under the NA hypothesis are below the actual 10% probability, sellers' average probability beliefs of disaster under the NA hypothesis do not differ significantly from 10% on average, and correspondingly sellers' implied probabilities are higher than buyers'.

Let p_b denote the buyers' perceived probability of a Disaster state and p_s denote the sellers' perceived probability of a Disaster state. Substituting into Equations (1)–(3), we get

$$E(d)_{\text{buyer}} = (1 - p_b)\text{ (remaining } N\text{-state's dividend)} + p_b\text{ (remaining } D\text{-state's dividend)}$$

$$E(d)_{\text{seller}} = (1 - p_s)\text{ (remaining } N\text{-state's dividend)} + p_s\text{ (remaining } D\text{-state's dividend)}$$

for the expected values of the common dividend under the FA hypothesis, and

$$E(d)_{\text{buyer}} = (1 - p_b)\text{ (remaining } N\text{-state's dividend)} + p_b\text{ (average of the } D\text{-state's dividends)}$$

$$E(d)_{\text{seller}} = (1 - p_s)\text{ (average of the } N\text{-state's dividends)} + p_s\text{ (remaining } D\text{-state's dividend)}$$

for the expected values of the common dividend under the NA hypothesis. Combining these equations with the private value and cost increments, we solve for market equilibrium prices and quantities for both models for all the combinations of probability beliefs (p_b,p_s) over $p_b = 0.01, 0.02, \ldots, 1$ and $p_s = 0.01, 0.02, \ldots, 1$. From these results we identify the range of probability beliefs of sellers and buyers in our experiments that could support the observed quantities and median prices for each period.

The median and range of probability beliefs for buyers and sellers supporting the observed quantities and median prices for each period's trades are shown in chronological order in Figures 14 and 15, separated by experiment. The dashed vertical lines mark occurrences of disaster states. Having added two degrees of freedom to our models, the choice between hypotheses becomes a matter of judgement and interpretation, rather than a test of predictions. Nevertheless, there are two features of these implied probability beliefs that tend to

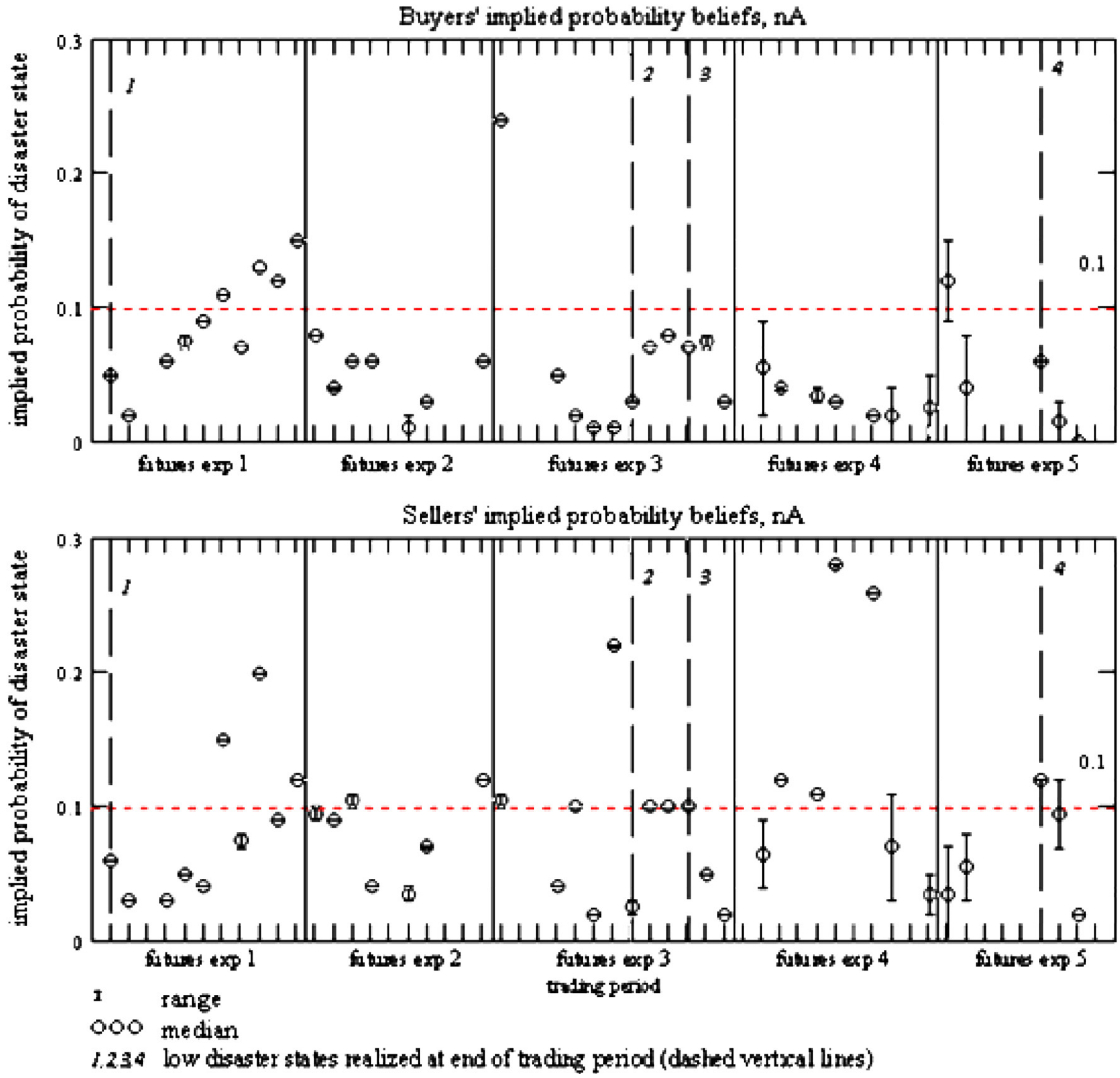

Figure 15. Buyer's and seller's implied probability beliefs under full-aggregation model.

support the conclusion that the NA model has more explanatory power:

- The implied probability beliefs calculated for the full-aggregation model are much sparser than those calculated for the NA model. This is because no combination of buyers' and sellers' probability beliefs support the observed prices and quantities in 25 out of 54 periods for the FA model, while the same is true in just 14 out of 54 periods for the NA model.
- Buyers' and sellers' implied probabilities vary more, and more erratically, over time, and vary more from buyer to seller, under the full-aggregation model than is the case under the no-aggregation model. This is likely an artifice of the data being forced to fit the model, rather than a true representation of the evolution of participants' probability beliefs. By contrast, the beliefs implied by the NA model tend to move together. Buyers' and sellers' implied beliefs tend to move in the same direction under the NA model, and period-on-period changes in beliefs tend to be much less extreme.

Clearly there is variation from period to period in both the buyers' and sellers' subjective beliefs. Table 5 gives some brief statistical analysis of the sets of beliefs under the NA hypothesis. For each statistic we conduct a hypothesis test that the mean

Table 5. Test of Mean Implied Probability Beliefs

Statistic	Mean	Standard deviation	Mean test statistic	p-value
Seller belief	0.089	0.062	−1.152	0.125
Buyer belief	0.059	0.046	−5.590	0.000

is equal to 10% versus the alternative that the mean is less than 10%. For the sellers' beliefs we fail to reject the null at all typical levels of significance, however for the buyer we do reject the hypothesis. We also conduct a t-test for difference in means for the two sets of beliefs. Here we reject the null hypothesis that the means are equal in favor of the alternative that the sellers' mean is larger than the buyers' mean. (The t-statistic is 2.469, has 78 degrees of freedom and a p-value of 0.008.) The strong negative bias possessed by buyers corresponds to similar results found in individual choice experiments, for example Slovic *et al.* (1977) and Kunreuther *et al.* (1978), in which subjects purchase insurance from the experimenter against small-probability, large-loss events.

Our experiment is the first in which some subjects *sell* insurance against small-probability, large losses. It also appears that changing the point of reference and the framing of the reinsurance task has eliminated this bias for sellers. However, there is another interesting perspective from which we can view these results. Instead of assuming that individuals are expected value maximizers who have probability biases, we could have assumed that they did not have subjective probability biases but that their preferences differ from risk neutrality. Under this interpretation we would conclude that the sellers give a greater assessment to the potential large losses of selling insurance contract than buyers give to the assessment of the large gains. This interpretation is consistent with the implications of the Kahneman and Tversky's (1979) prospect theory of decision making under uncertainty, where relative losses typically loom larger than relative gains.

CONCLUSION

In this paper we examine an insurance market's ability to generate equilibria which reflect the union of market participants' diverse information regarding the probabilities that govern states of nature. The correlation of prior information with market roles and the structure of uncertainty in these markets lead us to develop significant changes to the standard experimental design, introduced by Plott and Sunder (1988), used to test information aggregation. We found that the economic environment of a reinsurance market failed to generate the equilibrium predictions under either the FA model or the NA model. This is in contrast to Plott and Sunder's finding of information aggregation in simpler environments. In evaluating the hypotheses we found strong evidence that the value of the buyer's prior information had more impact on economic outcomes than did the seller's prior information. This suggested alternative explanations.

The uncertainty that characterizes insurance markets requires individuals to assess the value of small-probability, large-loss (gain) states. A plethora of past studies show that traditional expected utility theory's robustness falters in these situations, and that subjective probability biases or non-expected utility preferences can characterize behavior. In our setting one cannot distinguish between a subjective probability bias and a utility phenomenon. After we calculate the implicit subjective probability beliefs in our experiment we conclude that buyers possess a strong subjective probability bias and sellers do not. The corresponding utility explanation is that sellers' potential losses from reinsurance contracts loom larger than buyers' gains from reinsurance. Finally, after we control for these decision theoretic aspects, we see that the NA hypothesis has more explanatory power than the FA hypothesis.

These results do not provide optimism that insurance markets, such as the catastrophe futures index introduced by the CBOT in 1992, can lead to outcomes in which information is aggregated and risk is efficiently shared. Given the strong desirability of the information aggregation property in insurance market, it is worthwhile to explore whether other financial instruments (e.g. PCS option spreads and Act of God Bonds) and other institutions (such as the long standing bilateral contractual relationships that governed the reinsurance market prior to 1990) fare better than the market we study here.

Our results also suggest future directions in the study of information aggregation in general. Specifically, can we explain why the challenging decision making under uncertainty environment of catastrophe insurance impedes the information aggregation process? If we cannot answer this question, can we at least establish the boundary of this breakdown empirically? Furthermore, in previous experiments in which information aggregation occurs, the pooled information reveals the true state. In our experiments pooled information does not reveal the true state of nature, and it is of interest to assess the impact this has. Clearly, in most cases of interest, pooled information does not reveal the true state. Finally, we believe the introduction of the induced supply and demand approach to the study of markets with uncertainty is an innovation which may permit the performance of a wider class of experiments. The robustness of this approach needs to be more thoroughly tested.

NOTES

1. The property insurance market here is assumed to have little in the way of moral hazard. We believe this would muddle the central issue of information aggregation. Moreover, we feel secure in assuming that the market participant's actions do not exert significant influence over the probabilities of catastrophic events such as hurricanes, earthquakes, and floods.
2. See Nutter (1994), Marlett and Eastman (1997), Lecomte (1996), and Roth (1996).
3. O'Hare (1994) and Kunreuther (1997).
4. See Doherty (1997) for a good review of conditions in the insurance industry at the time.
5. D'Arcy and France (1992), Niehaus and Mann (1992), Harrington *et al.* (1995), Doherty (1996, 1997) discuss benefits of trading in catastrophe futures and insurance derivatives in general. Cox and Schwebach (1992), Cummins and Geman (1995) and Doherty (1997) also address the role of catastrophe futures markets in resolving information asymmetries.
6. Harrington and Niehaus (1999).
7. See Lecomte (1996), Nutter (1994), and Roth for examples of such institutional detail.
8. The unfortunate differences in the number of practice periods resulted from several experiments starting late due to tardy subjects.
9. For more details of the results from these three sessions see Plott and Sunder (1988, pp. 1100–1102).

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