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Replication and Efficiency in Experiments for Marketable Emissions Permits

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ABSTRACT

Replication and Efficiency in Experiments for Marketable Emissions Permits

The Energy Information Administration (EIA) funded the universities of Colorado and Arizona to define an experimental institution that captures the salient features of the sulfur dioxide allowance market created by the Clean Air Act Amendments of 1990 (CAAA); to develop and document a transportable software that implements the experimental institution; and to replicate experiments. Subsequently, EIA, in conjunction with the Oak Ridge National Laboratory (ORNL) funded the universities of Mississippi and Southern California to test the replicability of these experiments using statistically sound experimental design and the standardized software developed by the University of Arizona.

The present experiment is designed to identify any differences in the results of the two laboratory sites. It is designed to determine whether market outcomes are reproducible across different laboratories and experimenters and to determine if any behavioral patterns exist across a large set of independent experimental sessions.

Replication and Efficiency in Experiments for Marketable Emissions Permits[1]

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1. Introduction.

The Energy Information Administration (EIA) funded the universities of Colorado and Arizona to: define an experimental institution that captures the salient features of the sulfur dioxide allowance market created by Clean Air Act Amendments of 1990 (hereafter CAAA); develop and document a transportable software that implements the experimental institution; and replicate experiments.

Subsequently, EIA, in conjunction with the Oak Ridge National Laboratory (ORNL) funded the universities of Mississippi and Southern California to test the replicability of these experiments using a statistically sound experimental design and the standardized software developed by the University of Arizona. This report therefore employs experimental methods to evaluate the replicability of the experimental results, and performance and market outcomes in a comparable laboratory environment.

Some qualitative features of the field market are surprisingly similar to those we observe in

[1] The authors wish to express their appreciation to Dr. Douglas R. Hale of the DOE Energy Information Adminstration for his numerous contributions to this report.

our laboratory markets. The General Accounting Office report (GAO, 1994) notes that allowance prices are substantially below estimates provided by the EPA, a utility industry survey, and the Electric Power Research Institute (GAO, 1994, p. 36). The early trading in the field also suggests a price difference between the continuous search market and the annual EPA auction. Average prices were more than $275 per allowance prior to the March 1993 EPA auction, which cleared at the much lower price of $131 (with a mean price of $156). This information apparently surprised market participants, as trading virtually halted in the continuous market until about June of 1993. When trading resumed average prices rose above $200 during the summer of 1993, and fell to about $180 by February of 1994. The March 1994 EPA auction again generated prices significantly lower than the continuous market, with a mean price of $159 and a clearing price of $150 (GAO, 1994, pp. 34-35). The March 1995 EPA auction had a mean price of $132 and a clearing price of $130. Although the 1995 EPA auction prices are lower than the 1994 prices, they apparently are closer to the (now lower) continuous market prices; immediately after the 1995 auction an allowance broker claimed that the EPA auction "prices are within $10 of what I'm doing" (Utility Environment Report, 1995, p. 7). It is tempting to draw parallels with our experiment, because both the laboratory and the field prices appear lower than expected in early trading. Moreover, prices in our continuous market systematically exceed prices in the sealed-bid auction, but after several auctions the prices in the two institutions converge.

The present experiment is designed to identify any differences in the results of the two laboratory sites. The data generally indicate no differences in the two data sets, which provides evidence to support the hypothesis that results from these market experiments are not sensitive to subject pool and experimenter effects.

Below, Section 2 outlines the experimental design and theoretical predictions. Section 3 describes the trading institutions and experimental procedure. Section 4 reports the results of our testing of replication and market outcomes (prices, trading efficiency, and intertemporal banking) from the experiment. Section 5 presents our conclusions.

2. Experimental Design.

2.1. Market structure.

These experiments utilize a design that sets up four different firms loosely based on characteristics of the electrical power industry. This design consisted of two firm types; high and low; and two technology types; new and old. The firm size high and low refers to the production of BTU's. Old technology means higher abatements costs or greater sulfur dioxide emission per BTU and the new technology implies lower abatements costs or lower sulfur dioxide emissions per BTU. High firms are allocated more permits than Low firms, and old technology have higher values for permits than did new technology. Table 1 summarizes our experimental design, which parallels some key features of the CAAA and the naturally occurring field market.

At the beginning of an experiment which consisted of 12 periods of transactions, each subject within a firm is allocated \$20 as a starting balance[2]. In addition, permits are allocated to the firms by firm type. High (Low) firms are allocated 72(36) permits, 8 (4) for each of the first six periods and 4 (2) for each of the remaining six periods. All firms are required to submit 16% of their allocation for sale in the discriminative auction[3]. The number of trading periods and the uniform 50% allocation in the last six periods is common information, but the specific allocations and redemption values is private information.

Subjects within firms make profits either by redeeming the permits at the pre-assigned redemption values (see Appendix 1 for a summary of these parameters) or by selling the permits to other firms, in each of the transaction period. The permits can be traded either in a revenue-neutral sealed-bid discriminative auction, or in a double auction (i.e. a centralized exchange with a public bids, asks and prices). These markets will be discussed in greater detail below.

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[2] It should be noted that that with a few noted exceptions the units referred to in this report are in experimental dollars which are converted to U.S. dollars at the end of each session at a fixed, pre-announced exchange rate.

[3] As shown in Figure 1 below, and in the Appendix, our firms had a maximum of sixteen redemption values and a maximum allocation of eight permits per period. Using the 2.8% required by the CAAA, no firms would be required to submit permits to the revenue-neutral auction (8 x 2.8% = 0.22). We chose 16% so that at least some permits would be submitted to the auction, while ensuring that the required submission was small relative to the number of the respective firm's redemption values.

Table 1. Experimental Design

MARKET STRUCTURE

Number and Type of Firms: 8 firms, 2 of each type
Type 1. High output, Old emission technology
Type 2. High output, New emission technology
Type 3. Low output, Old emission technology
Type 4. Low output, New emission technology

Market Length: 12 trading periods

Per-period Permit Allocation
Periods 1-6: 8 per High output firm, 4 per Low output firm
Periods 7-12: 4 per High output firm, 2 per Low output firm

Required Contribution
to Revenue-Neutral Auction: [a]16% of per-period permit allocation
Periods 1-6: 1 per High output firm, 1 per Low output firm
Periods 7-12: 1 per High output firm, 0 per Low output firm

Computerized Auctions: Revenue-neutral sealed bid discriminative auction
"Free trade" continuous double auction

Steps in a Trading Period: 1. Allocation of permits
2. Withholding of 16% of permits
3. Double Auction
4. Revenue-neutral Auction
5. Redemption and banking decision

INDIVIDUAL SESSIONS[b]

University of Mississippi: UMS-1, UMS-2, UMS-3, UMS-4, UMS-5, UMS-6, UMS-7, UMS-8
University of Southern California: USC-1, USC-2, USC-3, USC-4, USC-5, USC-6, USC-7, USC-8

[a] No voluntary contributions allowed; see Footnote 7 of text.
[b] All subjects participated in a training session prior to participation in one of the Individual Sessions: see Section 3.2 of text.

2.2. Theoretical Predictions.

We have three theoretical benchmarks against which we compare our results: No-Trade, Myopic, and Intertemporal. At the No-Trade benchmark, firms simply redeem their permit allocations each period. A firm's profit is the sum of the redemption values for those permits allocated; there is no trading between firms. At the Myopic benchmark, firms attempt to maximize single period profits. Some trades occur, as allocated permits are redistributed from firms with low redemption values to those with higher redemption values. However, as in the No-Trade outcome, all permits are redeemed each trading period, so that no banking occurs. If the Myopic equilibrium is achieved, then the market price will be a one-time shift in prices beginning in period 7, as the market will adjust to the decrease in the allocation effective that period (the equilibrium predications are shown below in Table 2).

Table 2. Theoretical Predictions

	No-Trade	Myopic	Intertemporal
Permits Redeemed per Period			
Periods 1-6	24	24	36
Periods 7-12	48	48	36
Cumulative Permits Banked per Period[a]			
Periods 1-6	0	0	12t
Periods 7-12	0	0	12(T-t)
Market Price per Period			
Periods 1-6	--	300	[425, 450]
Periods 7-12	--	[550, 600]	[425, 450]
Aggregate Trading Profit per Period			
Periods 1-6	228.00	262.00	217.52
Periods 7-12	142.00	158.00	217.52
Total over all 12 periods	2220.00	2520.00	2610.24
Trading Efficiency per Period			
Periods 1-6	1.048	1.204	1.000
Periods 7-12	0.653	0.726	1.000
Total over all 12 periods	0.850	0.965	1.000

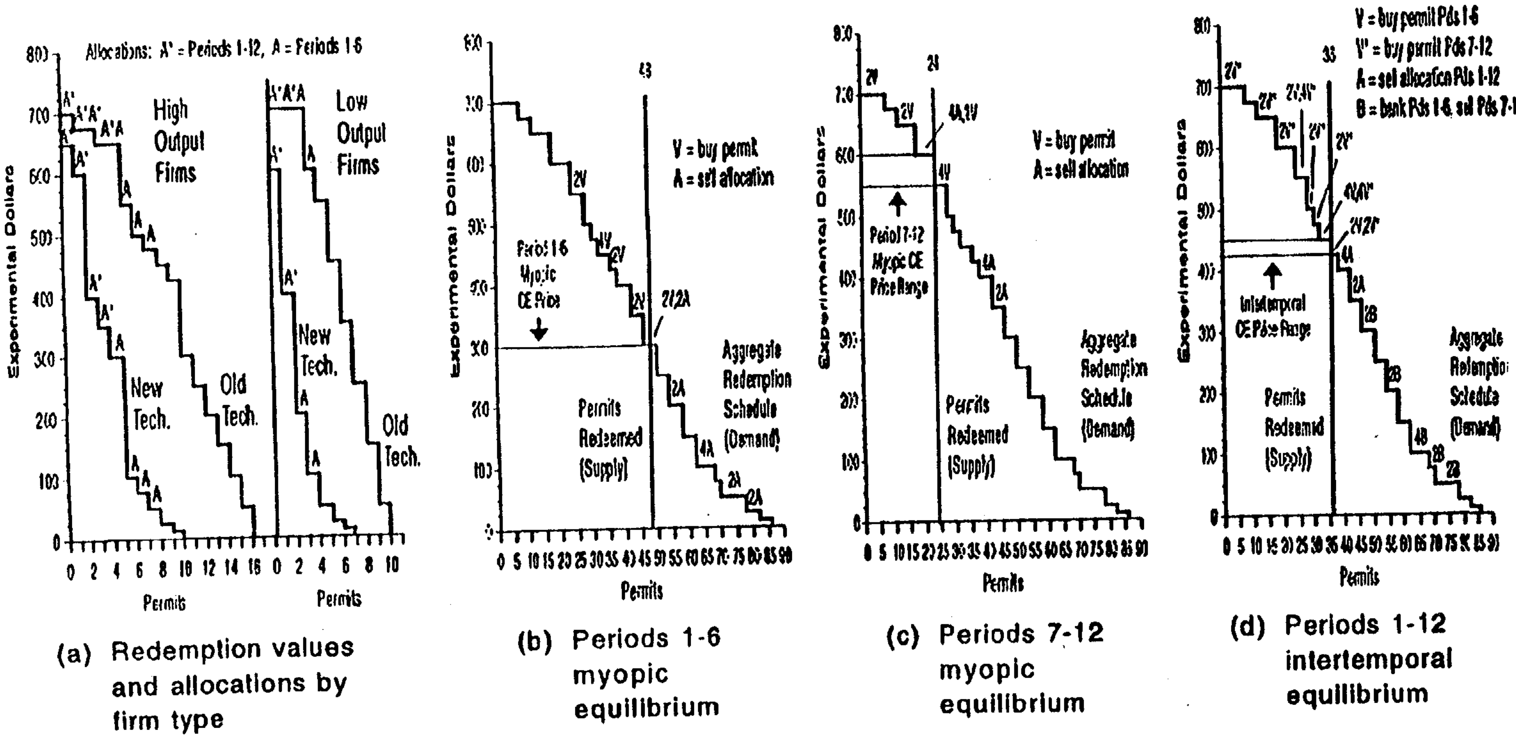
[a] t = trading period number 1,..., T where T = 12.

Finally, firms can maximize intertemporal profits by trading or redeeming some permits in the current period, and banking others for redemption or sale in later periods. At the Intertemporal benchmark, the traders exploit all gains from trade and optimally bank permits across periods. The market price and the number of permits redeemed is therefore constant across trading periods.

Figure 1 illustrates these theoretical predictions for our parameters. Panel (a) shows the per-period redemption schedules and allocations by firm type. For each firm, the redemption schedule represents the induced demand for permits. As discussed in the previous section, High output firms demand more permits than Low output firms *ceteris paribus*, and Old emission technology firms have higher redemption values than new technology firms *ceteris paribus*. Panel (a) also indicates the per-period allocations. Under the No-Trade outcome, firms would simply redeem their allocations for the associated redemption values.

Panels (b), (c) and (d) show the per-period induced aggregate demand and supply schedules. The demand schedule is the horizontal summation of the individual induced demand schedules shown in panel (a); recall that there are two firms of each type. The supply schedule is given by the number of permits to be redeemed per period. Under the Myopic outcome, the aggregate allocation is redeemed each period. In periods 1-6 (panel b), 48 permits are allocated each period, and in periods 7-12 (panel c), 24 permits are allocated each period (recall the 50% reduction in allocations, effective period 7). The Intertemporal outcome requires that the same number of permits be redeemed each period. As a total of 432 permits (= 6x48 + 6x24) are allocated across the twelve trading periods, 36 are redeemed each period. This implies that 12 permits should be banked each period in periods 1-6. In each of the last six periods, 12 banked permits are added to the aggregate allocation of 24 permits, so that total supply of permits is 36 (panel d).

In order for a given outcome to be Pareto efficient, the permits redeemed must be matched with the highest possible redemption values. For example, panel (b) shows that under the periods 1-6 Myopic outcome, the 48 permits must be matched with redemption values of 300 or greater. But inspection of panel (a) reveals that in periods 1-6, New technology firms are allocated permits that are matched with redemption values of less than 300, while Old technology firms have redemption values greater than 300 for which they are not allocated permits. Thus trades must occur between the Old and New technology firms to allow the maximal myopic gains from trade to be realized.



(a) Redemption values and allocations by firm type

(b) Periods 1-6 myopic equilibrium

(c) Periods 7-12 myopic equilibrium

(d) Periods 1-12 intertemporal equilibrium

Figure 1. Induced values and theoretical predictions.

A firm's maximum willingness to pay for a permit is the amount of the associated redemption value. Similarly, a firm's minimum willingness to sell an allocated permit is given by the amount the firm would receive if it simply redeemed the permit. Consequently, the competitive equilibrium price is determined by the intersection of the demand and supply schedules shown in Figure 1.

For example, in panel (b), those redemptions values that are greater than or equal to 300, but not matched with an allocated permit are denoted with a "V." Those redemptions values that are less than or equal to 300 and matched with allocated permits are denoted with an "A." If the market price is 305, there would be twelve permits for sale, but only ten would be bought. If the price is 295, there would be buyers for twelve permits, but only ten would be for sale. Only at a price of 300 is there zero excess demand.[4] Similarly, panel (c) shows that in periods 7-12, the Myopic competitive equilibrium is consistent with the range of prices [550, 600].

The Intertemporal competitive equilibrium is shown in panel (d). There, "B" denotes those permits that are banked in periods 1-6. In each of the first six periods, there are only six values greater than or equal to 450 that are not allocated permits, but there are eighteen permits that are allocated to values less than 425. However, after the 50% reduction in each of the last six periods, there are eighteen values greater than or equal to 450 that are not allocated permits, and only six permits allocated to values less than 425. Thus if twelve permits are banked per period in periods 1-6, and this balance is drawn down by twelve permits per period and put back on the market in periods 7-12, competitive forces will yield an equilibrium price range of [425, 450].[5]

Table 2 summarizes the per-period predictions under each of our benchmark outcomes. Profit and trading efficiency predictions are also included. Trading efficiency is expressed as a percent of

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[4] Those redemption values greater than 300 but not marked with a "V" are matched with an allocated permit. Similarly, those redemptions values less than 300 but not marked with an "A" are redemption values that are not matched with allocated permits. For simplicity, we denote only those values and permits that would result in trade at the competitive equilibrium.

[5] The reader will note that there is not a unique ordering of permits that must be banked, i.e., the intertemporal equilibrium requires only that 12 of the 18 permits allocated to values less than 425 be banked in periods 1-6. Numerous combinations meet this requirement. For simplicity, panel (d) of Figure 1 shows that the banked permits to be those matched with the lowest redemption values. These values are not allocated permits after the 50% reduction effective beginning period 7.

the Intertemporal equilibrium profits. Overall, the Intertemporal outcome has the highest aggregate profit, but in early periods when permits are banked, the per-period aggregate profit is higher under the No-Trade and Myopic outcomes. These predictions are the basis of our discussion of the results presented in Section 4.

3. Trading Institutions and Experimental Procedure

3.1. Trading Institutions.

As discussed above, trades could occur in either the double auction or the revenue-neutral auction. In the double auction (hereafter DA), firms negotiate bilateral trades on a public exchange. Firms may submit electronic bids and asks anytime during the auction (subject to inventory and cash constraints). The highest standing bid and lowest standing ask are displayed on each computer screen. A trade occurs when a buyer accepts the standing ask, or a seller accepts the standing bid. After a trade, both the standing bid and the standing ask are cleared, and the auction is open for new bids and asks. A history of prices is displayed at the bottom of the screen; all trades are for single permits.[6]

The revenue neutral auction (hereafter RNA) is a sealed-bid discriminative auction. At the start of the auction, the computer screen displays the number of permits for sale. Recall that each firm is required to withhold 16% of their per-period allocation for sale in the RNA; firms are not allowed to voluntarily submit additional permits for sale.[7] Next, firms submit private bids for permits. After all bids have been submitted, the computer ranks them from high to low. In periods 1-6 (7-12),

[6] The DA has proven to be a very efficient trading institution in a wide variety of laboratory market environments. See Davis and Holt (1993) for further discussion; for an exception see Van Boening and Wilcox (1995).

[7] Although the RNA3 software does allow subjects to voluntarily submit permits to the RNA, in addition to the involuntary submission, it does not allow subjects to assign a reservation price to any permits submitted to the RNA. Essentially, this procedure assigns a reservation price of zero. Under the CAAA, permits submitted involuntarily have a reservation price of zero, but permits submitted voluntarily may have a positive reservation price. As we felt that allowing voluntary submission without a reservation price was too far from the CAAA framework, we did not allow voluntary submission. Interestingly, in the RNA auctions conducted by the EPA to date, there have been few permits sold that were voluntarily submitted [U.S. GAO (1994), Utility Environment Report (1995)]. Furthermore, Cason (1993, 1995) shows that sellers in the EPA auction have an incentive to state reservation prices below their true cost of emission control, and Cason and Plott (1996) provide laboratory evidence that this can produce downward bias in EPA auction prices.

the highest eight (four) bids are accepted. Winning bidders pay the amount of their bid.

The total revenue collected from the RNA is then distributed to those firms who sold permits in the auction. The distribution is made on an average price basis: the total revenue is divided by the number of permits sold, and sellers receive that average price for each permit they sell. Thus the auction is "revenue neutral," as the auctioneer receives zero proceeds from conducting the auction, and all sellers receive the same per-unit price. This distribution scheme is identical to that mandated in the CAAA for permits forced into the RNA.

Therefore, in summary each trading period involved the same five basic steps (also refer to Table 1):

Step 1. Initial Allocation. At the beginning of each trading period, permits are allocated according to firm type.

Step 2. Required Withholding. All firms have withheld 16% of their allocation for sale in the RNA. Individual computer screens display the allocation, the required withholding, the number of banked permits from previous periods, and net holdings (= allocation + banked permits - required withholding).

Step 3. Double Auction. After all subjects review their permit holdings, the DA is opened and subjects are allowed to trade. The DA is closed after three minutes; the time remaining until the close is shown on the computer screens. After the close, current permit holdings are again shown on the individual computer screens. Subjects can also view a display of their redemption values.

Step 4. Revenue Neutral Auction. After all subjects review their permit holdings, the RNA is opened. Once all subjects have submitted their bids, the computer determines the winning bidders. The amount of the bid is deducted from each winning bidder's cash account, and the proceeds are redistributed amongst sellers on an average price basis (see above). After the RNA, the bids are displayed on the individual computer screens; winning bids are highlighted.

Step 5. Redemption and banking decision. Next, the individual screens display the current permit holdings and redemption values. Each subject indicates the number of permits to be redeemed, and the number to be banked as inventory for the next period. (The software allows subjects to experiment with different redemption and banking scenarios prior to making their final decisions.) Once all subjects make their redemption and banking decisions, their inventory and cash accounts are updated accordingly, and the market proceeds to the next trading period.

3.2. Experimental Procedure.

A session begins with an instruction period followed by a twelve period market. After all subjects arrive for the session, they are randomly assigned to a private computer carrel. Once everyone completes the self-paced computerized instructions, the first trading period begins. In the market, subjects can trade and redeem permits, using the RNA3 software, for experimental dollars. At the end of a session, each subject's net dollar holdings are translated into U.S. currency (paid in cash) using a private exchange rate. (The exchange rate is explained during the instruction period.) Subjects are paid their respective earnings and excused. In our sessions, earnings per subject were in the $20-$35 range, including a $5 "show-up fee" to encourage prompt arrival.[8] Our sessions lasted about two to two and one-half hours.

Previous pollution permit experiments have employed various methods to help subjects understand this relatively complex market (Elliott, 1993). In this study, potential subjects participate in a six-period training session, typically between one day and one week before participating in one of the "data" sessions shown in Table 1. The number of subjects per session ranged between four and twelve. (We allow the number of subjects to vary in these sessions, as our objective is training, not data collection.) There are four firm types with redemption values that are similar, but not identical, to those we use in our data sessions. Also, high (low) output firms receive eight (four) permits, and allocations are reduced by 50% after the midpoint period. Thus the training markets include the important characteristics of the data sessions.

Subjects that earn more than the "no trade" earnings are invited to participate in another session. The "no trade" earnings are the amount the subject would earn if he/she never traded permits, and simply redeemed her allocation at the end of each trading period. If a subject could earn more than this amount, then (apparently) she could use trading to his/her benefit. Over 80% of subjects that completed one of our training sessions met this qualification.

As shown at the bottom of Table 1, we ran sixteen replications of our market. Eight of those

[8] The exchange rates were chosen so that earnings in the intertemporal competitive equilibrium would cover the opportunity cost of participation in the experiment. Of course, whether or not that equilibrium was achieved depended on subjects' decisions. Also, one might argue that the opportunity costs of Los Angeles subjects differs from Oxford, Mississippi subjects. The nature of the study specified exact replication at the two separate sites. Thus we used the exact same parameters at both sites.

sessions were conducted at the University of Mississippi, and eight were conducted at the University of Southern California. Eight human subjects (two for each firm) participated in each individual session. The 128 subjects were women and men recruited from the respective school's business courses; most of the subjects were undergraduates, but a few graduate students also participated.

4. Results.

4.1 Replicability of Results.

The total profits calculated at the end of the final period were used to determine if the observed differences in estimated profits between universities, replications within universities, firms or technologies within replications, and subjects within firms (technologies) were random and were not subject to experimental bias (see appendix 2). A statistical technique called analysis of variance was used for this purpose. The object of this technique is to break up the total variation into components due to each of the factors and then compare them by the F-test. In this case the total variation was decomposed into variation between the universities, between replications within universities, between firms within replications and universities, between technologies within replications and universities, between subjects within firms, replications, and universities, between subjects within technologies, replications, and universities.

The averages for each cell and, within each university-specific replication, the averages for each type of firm and for each type of technology are readily obtained (Table 3). These yield averages across replications for each university. The results seem consistent across universities. The overall average for Mississippi was $315.06 and for Southern California was $312.21.

The effects of technology were similar, old having a profit greater than new of $138.89 and $151.52 respectively and the large firms gained more than the smaller by $160.08 and $169.65 respectively.

These findings are confirmed by the analysis of variance (Table 4). The small F-values show no significant difference between universities, and also that within a university there was not a significant difference between replicates. The differences between technologies and firms is highly significant.

Table 3. Observed Mean Profits in by Firms (High=H, Low=L) Technology, Replication (Rep) and University.

		University of Mississippi				University of Southern Cal.			
		Technology		Firm Means	Rep Means	Technology		Firm Means	Rep Means
Rep	Firm	Old	New			Old	New		
1	H	496.46	255.79	376.12		477.60	296.98	387.29	
	L	277.78	168.10	222.94		295.85	213.21	254.53	
	Mean	387.12	211.94		299.53	386.72	255.09		320.91
2	H	479.78	255.79	376.12		484.64	375.18	429.91	
	L	314.88	168.10	222.94		251.72	140.22	195.97	
	Mean	397.33	211.94		299.53	368.18	257.70		312.94
3	H	486.05	334.35	407.06		501.38	339.02	420.20	
	L	286.14	172.43	243.65		317.17	148.27	232.72	
	Mean	386.09	272.23		325.36	409.28	243.64		326.46
4	H	425.43	294.47	420.42		543.20	308.02	425.61	
	L	271.94	172.30	237.90		270.36	166.80	218.58	
	Mean	348.68	233.38		291.03	406.78	237.41		322.46
5	H	470.11	303.45	386.78		451.98	244.45	348.22	
	L	315.41	181.43	248.42		273.76	167.54	220.65	
	Mean	392.76	242.44		317.60	362.87	206.00		284.43
6	H	465.07	346.93	406.00		488.00	323.82	405.91	
	L	289.27	181.43	241.13		295.93	165.27	230.60	
	Mean	377.17	269.96		323.56	244.54	244.54		318.25
7	H	482.95	319.89	401.42		487.34	300.54	393.94	
	L	287.58	165.72	226.65		297.74	170.14	233.94	
	Mean	385.26	242.80		314.03	392.54	235.34		313.94
8	H	483.52	322.58	403.05		485.22	245.20	365.21	
	L	319.69	154.96	237.33		285.57	178.57	232.07	
	Mean	401.61	238.77		320.19	385.39	211.89		298.64
Overall Mean:		**Old**	384.50	**High**	395.10	**Old**	387.97	**High**	397.03

		New	245.61	Low	235.02	New	236.45	Low	227.38
University Mean				315.06				312.21	

Thus:

<u>*RESULT 1:*</u> *The profits earned by subjects do not differ by university or replications within universities.*

It is obvious from Table 4 that between universities variation is not significant because the observed value of .10 is smaller than the tabulated F-value of 4.49 at a 95% confidence level of significance for 1 and 16 degrees of freedom. This observation supports the hypothesis that the observed differences in the universities were due to chance (random) and were not subject to the experimental bias. This implies that these experiments are statistically replicable.

It is also clear from Table 4 that between replications within universities variation is not significant. Because the observed F- value of 0.58 is smaller than the tabulated F-value of 2.37 at a 95% confidence of level for 14 and 16 degrees of freedom. This supports the hypothesis that the observed differences in the replications were due to chance and were not subject to any experimental bias.

<u>*RESULT 2.*</u> *The results do differ by firm or technology.*

As expected, the between firms (technologies) within replications and universities variation is highly significant because the calculated F-value of 21.78 (16.81) is greater than the tabulated F-value of 3.37 at a 99 percent level of confidence for 16 and 16 degrees of freedom. It appears that the significant variation found among the firms (technologies) is induced by design.

<u>*RESULT 3.*</u> *The results do not differ by subjects within cells (firms+technologies).*

Table 4 shows that between subjects within cells (firms+technologies), within replications, and universities variation is not significant since the observed F-value of 0.81 is smaller than the tabulated F-value of 2.108 at a 95% confidence of level for 64 and 16 degrees of freedom. This shows there is no crossover effect between replications.

Because of the strength of these results, for the remainder of the analysis we pool the data across the 16 sessions at the two sites.

4.2. Theoretical Predictions.

For the following tests we employ t-tests and the non-parametric Wilcoxon tests, now based on the 16 independent observations contributed by the 16 sessions. Both the Wilcoxon test and the t-test are tests of central tendency of a distribution, that is, are the mean of a given sample the same or different from a theoretical prediction. The two test statistics generally agree but sometimes differ slightly in their statistical significance. We focus on the Wilcoxon test in reporting results below because, unlike the t-test, it does not require any distributional assumptions.

In this section we examine first the observed efficiency against the theoretical benchmark. We use as our measure of efficiency the subjects' aggregate profit as a percentage of the Intertemporal profit maximum. Other benchmarks tested include number of permits banked (and therefore the number redeemed), and the price of permits in both the DA and RNA auctions. The predictions

Table 4. Analysis of Variance

Sources of Variance	Degrees of Freedom (df)	Sums of Squares (SS)	Mean Sums of Squares (MSS)	F-value
Between universities	1	259.98	260	0.10
Between replications, within universities	14	20811.50	1487	0.58
Between firms, within replications, within universities	16	895028.03	55939	21.78
Between technologies, within replications, within universities	16	690747.98	43172	16.81
Between subjects within cells (firms+tech), within replications, within universities	64	132486.38	2070	0.81
Error	16	41087.01	2568	
Total	127	1780420.87		

follow from the experimental parameters selected for these experiments as seen in Appendix 1. Benchmark predictions are constructed assuming that each subject makes the optimal decision at all stages of the experiment. That is, each subject buys, sells, redeems and banks just as standard economic theory would predict.

Column (2) of Table 5 indicates that overall efficiency ranges from a low of 79.4 percent in UMS-1 to a high of 94.8 percent in UMS-3. All 16 efficiencies fall below the Myopic prediction of 96.5 percent, so the data strongly reject this Myopic efficiency benchmark. Thirteen of the 16 efficiencies exceed the no-trade benchmark of 85 percent, and the data also reject this theoretical prediction at the one percent level. We summarize this as:

RESULT 4. *Efficiency exceeds the no-trade prediction of 85 percent but falls below the Myopic prediction of 96.5 percent.*

One reason that efficiency often fails to improve substantially above 85 percent is that permit banking is far from optimal. Figure 2 summarizes the average banking balances by period across the 16 sessions relative to the intertemporal optimal benchmark. Recall that for the first 6 periods subjects should bank an additional 12 permits per period, and for the final 6 periods they should draw down this banked balance by 12 permits per period. The average balance of banked permits is less than one-half of this optimal level in periods 2 through 8, and the data reject the theoretical prediction in all but periods 1 and 2. Column (3) of Table 5 indicates that at the end of period 6 (when the optimal banking level is 72 permits) the banking balance ranges between 8 permits in UMS-5 to 65 permits in USC-4. This leads to:

RESULT 5. *Permit banking falls below the Intertemporal optimal level in every session. The corollary to this result is that permit redemption exceeds the Intertemporal prediction in periods 1-6 and falls below the Intertemporal prediction in periods 7-12.*

This low banking level could explain the pattern of prices across periods summarized in the next two results. Figure 3 presents the mean and 95 percent confidence intervals for the DA and RNA prices across the 16 sessions, by period. The mean DA prices begin above the Myopic prediction of 300 and within the Intertemporal range [425, 450]. However, the DA prices fall after period 2 and for periods 3 through 6 they are not significantly different from the Myopic prediction, and are significantly below the Intertemporal prediction.[9] After the reduction in permit allocations beginning in period 7, DA prices rise but never reach the Myopic prediction of [550, 600] by period 12. Instead, they seem to level out in the [450, 500] range. Yet, these prices "pass through" the Intertemporal prediction of 450 and rise significantly above it (using a Wilcoxon test at the 5 percent significance level) in periods 11 and 12. Though not shown here in the interest of brevity, the prices in only 4 of the 16 individual sessions appear to converge to the Myopic prediction by period 6, and in only 1 of the 16 sessions do prices converge to the Myopic prediction by period 12. We observe no convergence to the Intertemporal prediction in any of the 16 sessions. In summary:

RESULT 6. *DA prices move toward but fail to converge on the Myopic prediction in both the first 6 and final 6 periods. DA prices are not drawn to the Intertemporal price prediction.*

Figure 3 also illustrates that the RNA prices lie systematically below the DA prices in periods 1-6. The current focus is the comparison with the theoretical price predictions, and mean RNA prices lie significantly below the Myopic prediction in all periods 3 through 12. However, in periods 8 through 12 the mean RNA prices are significantly greater than or not significantly different from the Intertemporal prediction. The market-clearing RNA prices follow a similar pattern, summarized in the following final result:

RESULT 7. *RNA mean and clearing prices are significantly lower than the Myopic prediction in all periods after period 2, and are significantly lower than the Intertemporal prediction until period 8. After period 8, RNA mean and clearing prices are greater than or not significantly different from the Intertemporal prediction.*

5. Conclusion.

This paper achieves two primary objectives. First, it establishes that market outcomes are reproducible across different laboratories and experimenters even in a complicated environment with multiple trading institutions. While this may at first to many seem unsurprising, it should be noted

[9] A typographical error by one subject in period 2 of USC-1 led to a transaction at 9900, which explains the average price increase from period 1 to period 2. For these price hypothesis tests, we measure the (absolute) distance to the nearest endpoint of the predicted price interval. Prices within the predicted interval are coded with a deviation of zero.

Table 5: Summary of Banking Activity and Prices, by Session

			Periods 1-6			Periods 7-12		
Session Number (1)	Overall Efficiency[a] (2)	Aggregate Banking Balance in Period 6 (3)	Mean DA Price (4)	Mean RNA Price (5)	Mean RNA Clearing Price (6)	Mean DA Price (7)	Mean RNA Price (8)	Mean RNA Clearing Price (9)
UMS-1	79.4	27	290	255	171	170	199	174
UMS-2	93.6	25	313	202	163	428	410	375
UMS-3	94.8	22	351	300	240	475	490	461
UMS-4	83.1	28	365	230	149	494	486	455
UMS-5	91.2	8	221	177	112	488	514	483
UMS-6	93.0	29	350	240	173	526	499	472
UMS-7	90.1	28	355	309	228	385	477	418
UMS-8	92.0	43	345	323	280	410	432	387
USC-1	92.2	29	510	315	276	496	459	447
USC-2	89.8	20	403	428	346	505	483	445
USC-3	93.9	15	309	277	200	449	488	463
USC-4	92.6	65	284	228	189	312	277	252
USC-5	81.0	34	393	259	207	492	485	465
USC-6	91.4	21	330	199	152	459	404	389
USC-7	90.1	32	330	217	175	433	376	354
USC-8	85.4	22	249	274	163	477	532	495
UMS Avg.	89.7	26.2	324	254	189	422	438	403
USC Avg.	89.6	29.8	351	275	213	453	438	414
Grand Avg.	89.6	28	337	264	201	437	438	408

[a] Aggregate profit as a percentage of Intertemporal equilibrium profit.

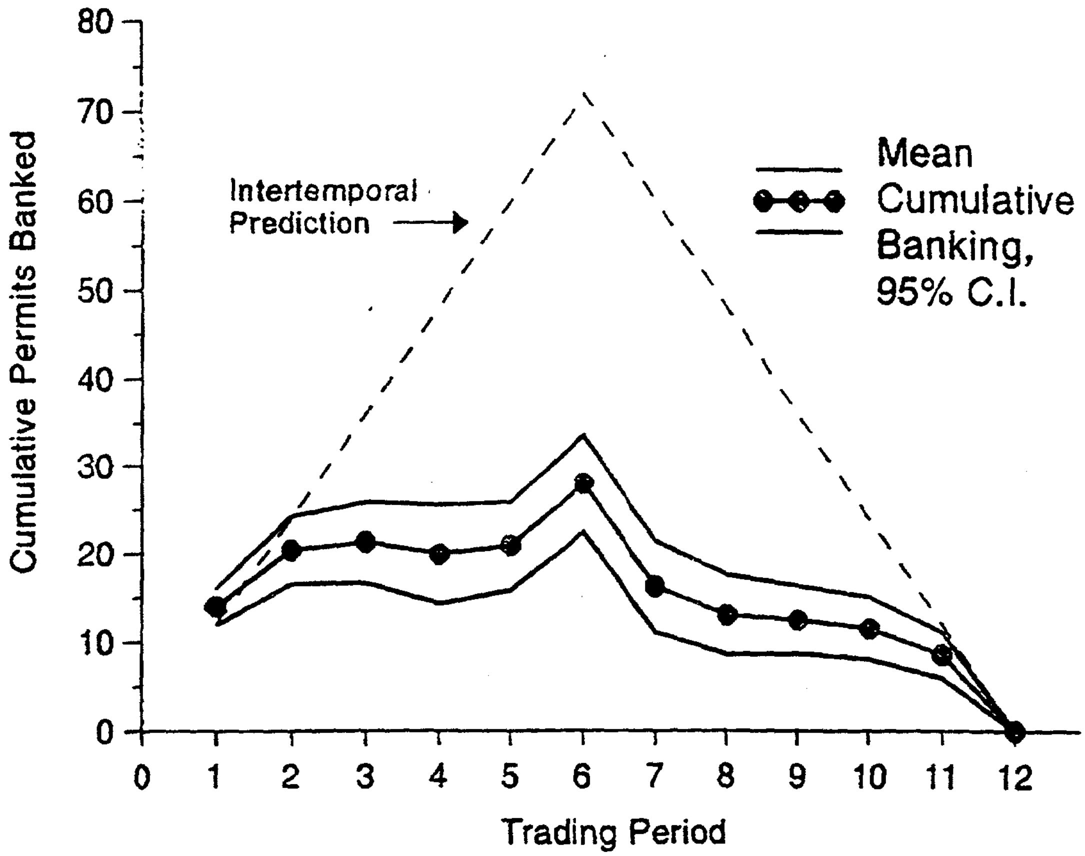

Figure 2. Mean banking balances by period.

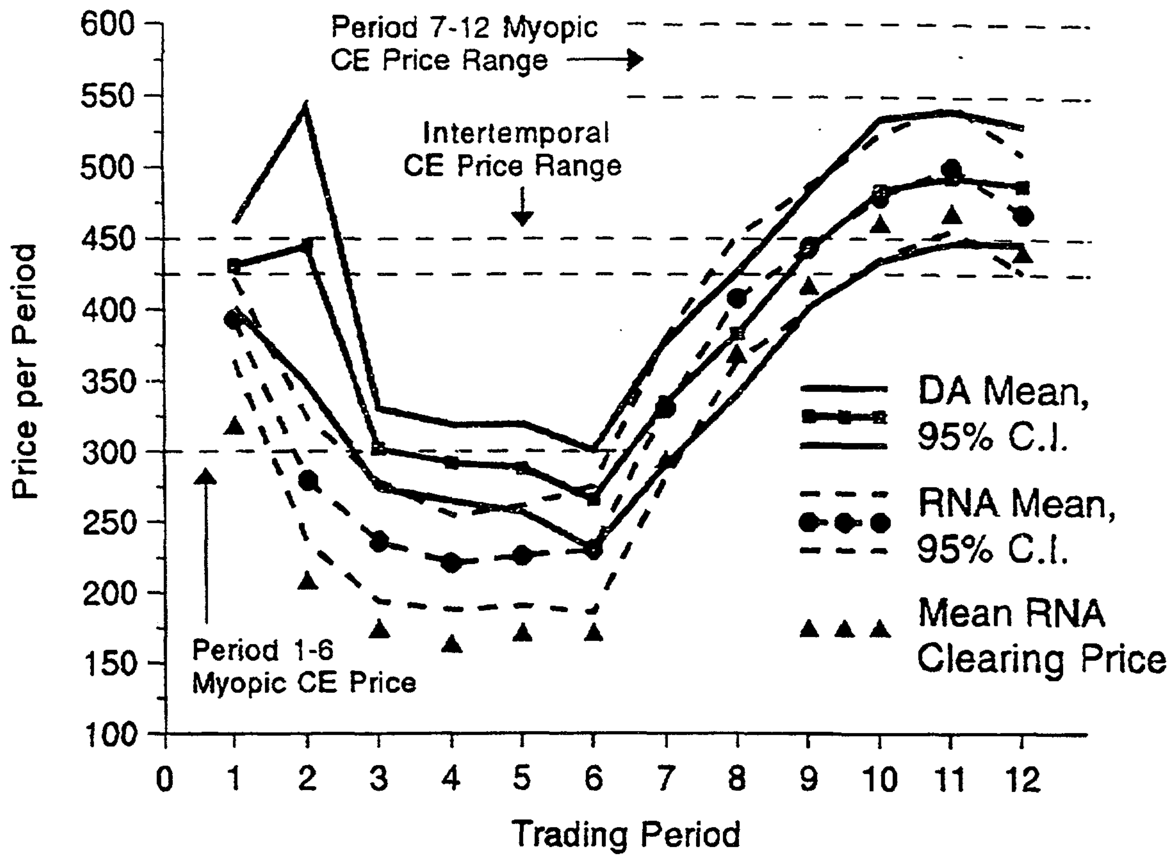

Figure 3. Mean auction prices by period.

The theoretical competitive equilibria for the Intertemporal and the Period 7-12 Myopic cases fall on an interval of price indeterminancy (see panels (c) and (d) of Figure 1). Thus, for these, the equilibrium price is shown as a range rather than a single value.

that replication of this type is not often undertaken in experimental economics research; even more rare are experiments that have replication as a central focus. We expect that other researchers in this field will, like us, take comfort in this finding.

Second, it identifies a remarkably robust behavioral pattern across a relatively large set of independent experimental sessions. Market prices typically fall short of (exceed) the intertemporal competitive equilibrium price prediction prior to (after) the pre-announced reduction in permits, and are drawn more closely to the myopic competitive equilibrium prediction. As discussed in the introduction, these price patterns are remarkably similar to the early experiences of the allowance market in the field. Of course, the experiment deliberately simplified the field environment in dozens of dimensions, so we draw these parallels with caution.

We see several valuable directions for follow-up work. The price disparity between the DA and the RNA may create an environment where speculative buying and selling of permits may be profitable. This type of speculative opportunity also exits between the early and late periods where the prices climb in response to the change in initial allocation. Both of these speculative opportunities deserve further in depth examination. Further, most laboratory studies have focused on one specific trading institution at a time, so most research questions regarding the interaction of trading institutions remain unanswered.

Finally, it may be useful to conduct experiments with additional features of the market institutions employed in SO_2 allowance trading in the field. For example, one could replace the continuous double auction market of the present experiment with a continuous brokered search market; and one could allow voluntary transmission of units to the sealed-bid auction with minimum asking prices and the pricing rules studied in Cason (1995). The EPA encourages trading in allowances with future effective dates, so it could be useful to conduct a simultaneous futures market. Porter and Smith (1995) found this to be an important treatment variable for controlling bubbles in their asset markets; perhaps a futures market could facilitate intertemporal equilibrium prices in permit markets.

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APPENDIX 1

Experimental Parameters

Output Level: Emission Technology:	High Old	High New	Low Old	Low New
Redemption Values				
Permit 1	700	650	700	600
Permit 2	675	600	700	400
Permit 3	675	400	700	200
Permit 4	650	350	600	100
Permit 5	650	300	550	50
Permit 6	550	100	450	25
Permit 7	500	75	350	12
Permit 8	475	50	250	
Permit 9	450	25	150	
Permit 10	425	12	50	
Permit 11	300			
Permit 12	250			
Permit 13	200			
Permit 14	150			
Permit 15	100			
Permit 16	50			
Allocations				
Periods 1-6	8	8	4	4
Periods 7-12	4	4	2	2

APPENDIX 2

The Observed Profits in Dollars by Subjects, Firm.
(High=H, Low=L), technology (TECH), replication (REP), and university.

		University of Mississippi		University of Southern Cal.	
		Technology		Technology	
Replication	Firm	Old	New	Old	New
1	H	440.28	239.55	464.32	253.26
		552.64	272.02	490.87	340.70
	L	400.00	173.52	301.99	149.86
		155.56	162.68	289.70	276.55
2	H	482.20	353.25	461.56	391.11
		477.35	315.44	507.72	359.25
	L	294.74	171.26	195.61	89.94
		335.01	173.60	307.82	190.49
3	H	481.67	354.45	525.44	337.63
		490.43	355.14	477.32	340.40
	L	275.02	185.95	312.23	156.10
		297.25	193.37	322.11	140.02
4	H	375.43	330.48	561.25	287.02
		475.43	258.46	525.15	329.02
	L	249.58	194.32	339.19	163.99
		294.29	150.27	201.52	169.60
5	H	516.98	306.97	504.48	327.12
		423.23	299.92	399.48	161.78
	L	330.26	176.51	279.76	184.61
		300.56	186.34	267.76	150.47
6	H	445.24	337.43	509.55	304.75
		484.89	356.43	466.44	342.88
	L	302.85	197.56	290.25	154.75

		275.68	188.42	301.60	175.77
7	H	455.87	361.52	473.11	269.75
		410.02	278.25	501.56	331.13
	L	333.89	182.46	298.88	188.32
		241.26	148.98	296.88	151.95
8	H	445.94	358.51	475.77	253.11
		52.10	286.64	494.67	237.29
	L	316.90	157.22	275.23	177.73
		322.48	152.70	295.90	179.41

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