A Laboratory Comparison of Uniform and Discriminative Price Auctions for Reducing Non-point Source Pollution

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ABSTRACT. *Auctions allow regulators to identify land management changes with substantial environmental benefit and low opportunity cost. This paper reports an experiment in which seller subjects compete in sealed-offer auctions to obtain part of a fixed budget allocated by the experimenter-regulator to subsidize pollution abatement. One treatment employs uniform-price auction rules, whereas another treatment employs discriminative price auction rules. We find that most offers in the uniform-price auction are within 2% of cost, whereas most offers in the discriminative price auction are at least 8% greater than cost. Nevertheless, the discriminative-price auction has superior overall market performance.* (JEL C91, Q15)

I. INTRODUCTION

Auctions are commonly used to allocate scarce resources. Recent applications of economic theory and experimental economics to auction design have substantially improved the performance of auctions and have also helped to expand their applications to a broad range of problems. One area where auctions have attracted attention is in allocating resources to protect the environment. Many environmental problems stem from agricultural land management practices. These include rising salt and nutrient levels in rivers and bays, wetlands degradation, destruction of remnant vegetation, and dryland salinity. These pollution problems cause a decline in pasture and crop productivity, stunted growth, and decreased plant yields. Extreme salinity can leave soil barren, for example, supporting only isolated patches of the most salt-tolerant plants. Non-point sources in agriculture generate a substantial fraction of certain types of pollution, and it is difficult or prohibitively expensive to identify the amount and the source of many of these non-point emissions. Landowners have more information than regulators about their production plans and their costs of reducing pollution. An incentive mechanism such as an auction is well suited to address this information asymmetry and encourage different landowners to reveal their private opportunity cost of land management changes. This could help the regulator to identify the land use options with greater environmental benefit but lower opportunity cost.

The theoretical advantages of auctions to address environmental problems are well recognized (e.g., Latacz-Lohmann and Hamsvoort 1997). However, using auctions to solve environmental problems in practice requires more empirical research. In this paper, we use experimental methods to examine two kinds of auction designs for "en-

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vironmental procurement"—uniform-price auctions and discriminative-price auctions. Landowner sellers offer projects that generate environmental improvement in these auctions. Specifically, sellers offer projects with different costs and different levels of environmental benefits to the regulator, who is the buyer. The regulator then ranks the offers on the basis of their prices and on their potential for environmental improvement. The regulator allocates a fixed monetary budget to buy a maximum of one project from each seller. Each project is a specific land use change. We use this environmental terminology for motivating and describing the experiment.

However, it is important to recognize that no actual landowner or regulatory agency participated in the experiments reported in this paper, and no actual environmental benefits were realized. Instead, as is usual in experimental economics, student subjects played the role of the field participants (landowner-sellers) and the experimenter played the role of the regulatory authority. Subjects received real monetary rewards based on the profits earned from their decisions, but only artificial benefits and projects were purchased by the experimenter.

All sellers submitted sealed offers, and in the uniform-price auction the successful sellers received a uniform price (per unit of environmental benefit) equal to the lowest rejected offer. In the discriminative-price auction, each successful seller received the actual price offered, rather than a single price common to all sellers. In the discriminative-price design, the sellers face uncertainty about acceptance, but not about price, since the price obtained from the regulator equaled the offer if the offer is accepted. When contemplating raising her offer, a seller trades off the decreased probability of acceptance against a higher trading surplus conditional on acceptance. She has an incentive to misrepresent her costs and submit offers higher than her true reservation values, because otherwise she would earn no trading surplus.

By contrast, in the uniform-price auction, all the successful sellers received market-clearing prices that exceeded their offers and that is set by a seller who does not trade. In these auctions, each seller has a greater incentive to reveal her true costs, since submitting an offer greater than the cost of a unit lowers the probability of selling that unit, but does not raise the price at which the item might be sold. We find that offers are substantially closer to costs in the uniform-price auction compared to the discriminative-price auction. Nevertheless, for the experimental parameters we employ, the overall performance of the discriminative-price auction is superior.

Formal analysis of sealed bid auctions dates back to Vickrey (1961), who compared the incentives resulting from different auction procedures. He obtained a seminal revenue equivalence theorem, which states that under the assumptions of bidder risk neutrality, independent private valuations, symmetry among buyers, single unit demand, payments a function of bids only, and zero transaction costs incurred in bid creation and implementation, some different auction formats yield the same expected revenue to the auctioneer. Much of the theoretical literature following Vickrey examines the robustness of this result to the introduction of alternative assumptions about buyers and sellers.[1] Empirical research comparing uniform-price auctions and discriminative-price auctions has used both field data and data from laboratory experiments. Kagel (1995) provides a survey of the early auction research. Smith (1982) reports the results of a number of experiments for multi-unit auctions in which the bidders submit single unit bids. The results neither support nor refute the revenue equivalence theorem. Cox, Smith, and Walker (1985) find that subjects failed to follow their dominant strategy of bidding equal to value in multiple-unit, uniform-price, sealed bid auctions. Cox, Roberson,

[1] This body of research does not provide conclusive evidence on which kind of auction would theoretically provide higher revenue and be more efficient. The results are critically dependent on the assumptions made. Holt (1980), Maskin and Riley (2000), Milgrom (1989), Bikhchandani and Huang (1993), and Back and Zender (1993), to cite a few, examine different features of buyer behavior in single and multi-unit auctions.

and Walker (1982) and Kagel, Harstad, and Levin (1987) provide laboratory evidence that subjects respond strategically to the different incentives that alternative auction formats generate. Tenorio (1993) uses data from the Zambian foreign exchange auction to analyze the effects of a change in auction format from uniform price to discriminative price and finds that after controlling for other factors, the uniform-price format yields higher average revenue than the discriminative-price format. Umlauf (1993) reports similar results for auctions undertaken by the Mexican treasury.

Theoretical research on auctions cannot be directly applied to the auctions in this environmental application, however, because environmental goods and services violate many of the assumptions for the revenue equivalence theorem. For example, the auctions studied here assume that sellers can offer multiple projects for sale, but because of the interaction of the environmental benefits across projects we impose the restriction that the buyer would purchase at most one project from each seller. The interaction of benefits occurs, for example, because implementing project 1, the installation of grassed swale drains with sediment traps to reduce nutrient loads would reduce the environmental benefit of project 2, decreased fertilizer applications. Although the benefits of these two alternative mitigation strategies are interrelated, the buyer in our auction algorithm evaluates them separately. To minimize the impact of these project interactions, we limit each seller to supply at most one project. Another reason for imposing this limitation is that regulatory authorities might want to increase participation in the conservation program, and this restriction increases each individual seller's likelihood of success in the auction. Note that even though a maximum of one project is bought from each seller, the project size and its environmental benefits differ significantly across sellers. Note also that because they can sell no more than one project, sellers may not submit offers independently for each project. Instead, they could infer that certain projects have a higher potential probability of winning and therefore they might focus their efforts on obtaining profits on these projects. Since they know that the buyer will purchase at most one project from each seller, they could make less aggressive offers on their other projects so as to avoid competing with themselves across projects.[2] Moreover, the fixed budget constraint for the auction implies that the number of projects accepted is endogenous. Hence, our environment is not consistent with any particular existing theoretical model, and it is unlikely that any new tractable theory could capture these complications that arise in most relevant field applications.

Fortunately, in spite of these realistic complications, it is feasible to compare the two auction institutions empirically even though a theoretical comparison is not practical. In our laboratory testbed, we compare the behavior and performance of these two auction institutions in two different controlled environments. Our results show that laboratory subjects understand the cost revelation incentives of the uniform-price auctions, with most submitted offers near the actual costs. By contrast, in the discriminative-price auction almost all offers are greater than cost. For the parameters we employ, however, the discriminative-price auctions result in more efficient environmental protection than the uniform-price auctions. All three performance indicators show that the discriminative-price design leads to significantly greater overall performance, even though the discriminative-price auction rules lead to higher offer prices. The empirical research issues examined in this paper are

[2] Our results, however, suggest that sellers do not seem to focus on making an aggressive, realistic offer for only one of their projects, even though this is an option available to them. We speculate that this behavior occurs because, as discussed below, sellers do not know how the buyer evaluates the benefits associated with individual projects. It would be feasible to model the interaction of the benefits provided by different projects and relax the restriction that sellers can sell at most one project. But since this interaction would be complicated to explain to subjects, we chose to impose the restriction in this initial study and leave investigation of the benefit interactions to future research.

crucial to improving our understanding of how these environmental auctions might perform in the field. The experiments are based on parameters calibrated to field applications for actual environmental problems, so we think they can provide valuable guidance in economic settings such as these where theoretical research cannot give clear predictions and hence is of limited use to make institutional comparisons.

The rest of the paper is organized as follows. Section 2 describes the experimental design and Section 3 presents the results. Section 4 concludes with a brief discussion of the findings.

II. EXPERIMENTAL DESIGN

Environment and Procedures

As discussed above, the revenue equivalence theorem does not apply in this environment, so it is possible that the relative efficiency and performance of the two auction institutions might be sensitive to the specific parameters chosen for the laboratory testbed. This potential parameter sensitivity is not uncommon in laboratory research, but it is more relevant here because we wish to strengthen the external validity of our results for potential field applications. We therefore employ parameters that correspond to two different non-point source pollution problems—nitrogen reduction and salt reduction. The costs and environmental benefits are estimated specifically for these two environmental applications. In particular, in the nitrogen reduction environment, we employ cost and quality parameters representing the estimated opportunities for environmental improvement through land use change in the Port Phillip watershed, in southern Victoria, Australia (also see Cason, Gangadharan, and Duke, 2003). All subjects have their costs and quality drawn from broadacre (field cropping) and grazing land uses, which are the activities that represent the largest land use in the watershed (57% of the land) and contributes to 53% of annual nitrogen pollution. In the salinity reduction environment, the costs of salt management options and the associated environmental benefits were obtained from the Kamarook Catchment in Victoria, Australia (Hekmeijer et al. 2000).

Subjects make offers based on different costs and qualities to represent the heterogeneity across different activities on the same land and between the same activities on different plots of land. We introduce heterogeneity by drawing costs and environmental benefits for each land use change independently for each seller, each period, from the uniform distributions based on the ranges shown in Table 1.[3] We use the same sequence of drawn values in all the sessions to minimize across session variation and to improve the power of our comparison across auction institution treatments. Sellers know their costs, but they do not know how the buyer values the benefit provided by each project. This is a reasonable assumption, as in the field landowners would not have accurate information about the relationship between various land management changes and their corresponding environmental benefits. Regulators, however, may have a relative advantage in obtaining this information as they work with biophysical modelers, hydrologists, and others with the relevant expertise. We also do not reveal the benefits to sellers in the experiment because a primary conclusion of Cason, Gangadharan, and Duke (2003) was that this information led sellers to misrepresent their costs more for high-benefit projects, and this reduced total abatement and lowered other performance characteristics of the auction.[4] In order to enhance the external validity of the experiment, we also do not provide

[3] The benefit ranges shown in Table 1 represent the best available estimates given the soil type and topography of the Port Phillip watershed and the Kamarook Catchment. The cost ranges were developed through consultation with private landholders. For additional details on costs and benefits for nitrogen reduction, see Cason, Gangadharan, and Duke (2003).

[4] There might be some situations in which the regulator would want to reveal the environmental benefits to sellers in the field. Revealing the benefits could, e.g., educate landowners about the best land use option, promote community participation in voluntary environmental programs, and increase the credibility of the auction mechanism as more information would lead to perception of fairness and transparency.

TABLE 1

COST AND ENVIRONMENTAL BENEFIT QUALITY: PARAMETERS

Panel A: Nitrogen Reduction

Land Use or Management Change	Cost Range	Nitrogen Reduction Range
Filter/buffer strips	\$15–65 per ha/year	0.35–0.875 kg/ha/year
Stabilize soil erosion	\$15–65 per ha/year	0.28–1.05 kg/ha/year
Best management practices	\$17.5–65 per ha/year	0.35–0.70 kg/ha/year

Sources: Argent, R. M., and V. G. Mitchell. 1998, *FILTER: A Nutrient Management Program for the Port Phillip Catchment*. Centre for Environmental Applied Hydrology, University of Melbourne, Melbourne, Australia; Rendell McGuckian Consultants. 1996. "Documentation of 'Best Management Practices' for Nutrient Reduction and Management in Dryland and Irrigated Agriculture." Report for the Department of Natural Resources and Environment, Victoria, Australia.

Panel B: Salinity Reduction

Land Use or Management Change	Cost Range	Salt Reduction Range
Wheat/canola rotation phased with annual pasture changed to a wheat/canola rotation phased with Lucerne (shallow rooted)	\$123–152 per ha/year	24 mm-33 mm per year
Wheat/canola rotation phased with annual pasture changed to continuous Lucerne (deep rooted)	\$202–221 per ha/year	36 mm-44 mm per year
Wheat/canola rotation phased with annual pasture changed to continuous kikuyu pasture	\$252–271 per ha/year	31 mm-56 mm per year

Sources: Salt management options are obtained from Read-Sturgess Associates. 2000. "Quantitative Analysis of Benefits and Costs for Salinity Control." Report for the National Land and Water Resources Audit, Theme 6, Project 3.3. Victoria, Australia.

Note: Each of the eight sellers drew costs and benefits for three land use or management changes, one from each of the three categories indicated below. For the nitrogen reduction sessions, these costs and benefits were scaled up to correspond to 150 ha in land area per seller. We did not scale up the values for the salinity reduction sessions.

sellers with any information about other sellers' costs and benefits or the distributions that are used to generate the costs and benefits. They are told simply that the costs and benefits levels would be different across sellers and could change from period to period. They also do not know the buyer's budget, which is fixed at \$25,000 experimental dollars per period in the nitrogen reduction environment and \$1,000 experimental dollars per period in the salt reduction environment. Subjects are informed that the experimenter purchases the lowest priced items per unit of quality, spending the fixed budget in each period. At the end of each auction period, sellers only learned which item (if any) they sold and the price they received.

The design of the experiment employed in this paper has some similarities to the experiment described in Cason, Gangadharan, and Duke (2003). Both experiments use abatement cost and environmental quality parameters from the field and both are auctions where the sellers can sell a maximum of one unit each period.[5] The current experimental design differs in many other ways from that in Cason, Gangadharan, and Duke (2003), however. All the auctions in Cason, Gangadharan, and Duke (2003) use a discriminative pricing rule, whereas in this paper we compare discriminative and uniform pricing rules. Casan, Gangadharan, and Duke (2003) include multiple auction rounds in each period, in which sellers could revise offers after learning whether any of their projects were tentatively accepted. Only one round of offers was conducted each period in the current paper. Casan, Gangadharan, and Duke (2003) allow subjects to communicate verbally between auction periods to verify that the auction rules are robust to collusion opportunities, while we did not allow any

[5] Casan, Gangadharan, and Duke (2003) use field data relating to nitrogen reduction only, whereas in this paper we use data for nitrogen and salt reduction. This broadens the potential application of our results.

communication in the present study. Finally, Casan, Gangadharan, and Duke (2003) focus mainly on identifying the information conditions that would allow the regulator to award land management contracts to maximize pollution abatement for a fixed-auction budget, and they find that when environmental benefits are revealed to sellers, the total abatement is lower. As noted above, in this paper we never reveal the environmental benefit to sellers.

Experimental subjects are undergraduate students from Purdue University and the University of Melbourne. All participated in only one session reported here and had no previous experience in sealed-offer auctions. We report 30 sessions, 15 conducted at Melbourne (8 in the uniform-price auction format and 7 in the discriminative-price auction format) and 15 conducted at Purdue (7 in the uniform-price auction format and 8 in the discriminative-price auction format). All sessions have 36 trading periods. In each session, 8 seller subjects offer items in a computerized, sealed-offer auction, so across all 30 sessions a total of 240 different subjects participated. In each auction period, sellers can offer to sell three items that correspond to different land use changes and have different environmental benefits. Sellers submit offers using an electronic form on a Web browser. After all offers are submitted, the server sorts the offers and ranks them on the basis of the offer price and the quality of the items (quality is the environmental benefit) and calculates the allocation for the period. The auctioneer buys the lowest-price projects per unit of quality, subject to the constraint that at most one item is bought from each seller and total auction expenditures are no greater than the auction budget. The two auction institutions differ only in how they determine trading prices; see Table 2 for a specific example. Once the allocation is made, the results are reported to the subjects electronically on their Web browsers.

As is usual in experimental economics, we use neutral terminology in the instructions to refer to the different items that sellers could offer. The instructions for the experiment are available at http://www.mgmt.purdue.edu/faculty/cason/papers/uniland_inst.pdf. Subjects are asked to record the profits made in each of the 36 periods in their record sheets and they are paid privately in cash after the experiment. The conversion rate used in the nitrogen reduction environment for the Purdue sessions was 1,000 experimental dollars = 1 U.S. dollar and the conversion rate used in Melbourne was 600 experimental dollars = 1 Australian dollar. For the salinity reduction sessions the corresponding conversion rates were 15 experimental dollars = 1 U.S. dollar and 12 experimental dollars = 1 Australian dollar. Sessions typically lasted 60 to 90 minutes, including the instruction time. Average subject earnings were about US$23 each in the Purdue sessions and A$30 each in the Melbourne sessions.

Treatments and Predictions

Our goal in this experiment is to compare the performance characteristics of uniform-price auctions and discriminative-price auctions. In the uniform-price treatment, if sellers sell an item they receive a price that is greater than, or equal to, their offer price. The uniform price in the market is determined by the lowest price per unit of quality submitted by a seller who had all of his or her offers rejected. In the discriminative-price treatment, sellers receive their exact offer price when they sell an item. Both auctions employ the *greedy algorithm* that finds the best local solution by accepting the items that have the lowest price per unit of quality, subject to the other constraints that (1) no more than one item is purchased from each seller; and (2) total expenditures do not exceed the overall auction budget.[6]

Table 2 presents an example from period 31 in two sessions to illustrate the

[6] We could have implemented a more complex algorithm that is more likely to find the globally optimal solution, but at the cost of not being able to explain the auction purchase rule to sellers. We chose this simple algorithm since our goal is to study auction rules that could be implemented in the field with a reasonable level of transparency.

TABLE 2
Example Costs, Environmental Benefits, and Offers for Two Sessions (Period 31)

Period	Seller ID	Project "Color"	Environmental Benefit	Project Cost	Offer	Offer/Benefit Ratio	Ratio Ranking	Price-setting Ratio	Project Sold?
				Discriminative Price Auction					
31	1	blue	73.19	6120	7219	98.63	19		
31	1	red	124.46	2889	3988	32.04	1		Yes
31	1	yellow	79.85	5377	6476	81.10	17		
31	2	blue	55.99	4818	4988	89.09	18		
31	2	red	153.41	9047	9247	60.28	9		
31	2	yellow	95.24	7265	7410	77.80	16		
31	3	blue	80.64	8698	9200	114.09	20		
31	3	red	68.07	3089	3900	57.29	8		
31	3	yellow	97.7	5960	6600	67.55	12		
31	4	blue	91.66	4901	6901	75.29	15		
31	4	red	111.26	5688	7600	68.31	13		
31	4	yellow	79.51	8772	11777	148.12	24		
31	5	blue	98.3	2848	3600	36.62	2		Yes
31	5	red	85.86	2969	3500	40.76	3		
31	5	yellow	84.45	4687	5200	61.57	10		
31	6	blue	74.3	3287	4200	56.53	7		Yes
31	6	red	153.19	9037	10000	65.28	11		
31	6	yellow	86.11	9380	10200	118.45	22		
31	7	blue	91.9	6117	6617	72.00	14		
31	7	red	126.03	6217	6717	53.30	6		Yes
31	7	yellow	77.04	9689	10000	129.80	23		
31	8	blue	124.42	4859	6000	48.22	4		Yes
31	8	red	53.34	4899	6200	116.24	21		
31	8	yellow	102.6	3691	5000	48.73	5		
				Uniform Price Auction					
31	1	blue	73.19	6120	6255	85.46	19	49.33	
31	1	red	124.46	2889	2999	24.10	4	49.33	Yes
31	1	yellow	79.85	5377	5888	73.74	18	49.33	
31	2	blue	55.99	4818	4100	73.23	17	49.33	
31	2	red	153.41	9047	8500	55.41	12	49.33	
31	2	yellow	95.24	7265	6500	68.25	16	49.33	
31	3	blue	80.64	8698	8698	107.86	21	49.33	
31	3	red	68.07	3089	3090	45.39	8	49.33	Yes
31	3	yellow	97.7	5960	6500	66.53	14	49.33	
31	4	blue	91.66	4901	4901	53.47	11	49.33	
31	4	red	111.26	5688	5688	51.12	10	49.33	
31	4	yellow	79.51	8772	8772	110.33	23	49.33	
31	5	blue	98.3	2848	1500	15.26	2	49.33	Yes
31	5	red	85.86	2969	1600	18.63	3	49.33	
31	5	yellow	84.45	4687	2500	29.60	5	49.33	
31	6	blue	74.3	3287	3300	44.41	7	49.33	Yes
31	6	red	153.19	9037	9050	59.08	13	49.33	
31	6	yellow	86.11	9380	9400	109.16	22	49.33	
31	7	blue	91.9	6117	6117	66.56	15	49.33	
31	7	red	126.03	6217	6217	49.33	9	49.33	
31	7	yellow	77.04	9689	9689	125.77	24	49.33	
31	8	blue	124.42	4859	4200	33.76	6	49.33	
31	8	red	53.34	4899	5000	93.74	20	49.33	
31	8	yellow	102.6	3691	1	0.01	1	49.33	Yes

rules. In both auction formats, the algorithm first calculates ratio of the offer price to the benefit for each project, and then prioritizes projects according to this ratio from lowest to highest. The top panel of Table 2 shows this ranking and allocation for a discriminative price session. The first and second projects in this ranking are sold, but the third is not because the algorithm already bought a project from seller 5. The auction only purchases five projects because the cumulative cost is $24,505 and no additional projects can be purchased with the $495 remaining in the auction budget. The bottom panel of Table 2 shows results in a uniform price session. Again, only five projects are sold. All are sold at the offer/benefit ratio of a seller (7) who submitted the lowest ratio (49.33) but had all of her offers rejected. For example, instead of his red-unit offer of $2,999, seller 1 received 49.33 times his environmental benefit ($124.46) = $6,140 for this project. Total auction expenditures are $23,073 this period.

The standard revenue equivalence results do not apply in these auctions since sellers have multiple items to offer, they do not observe the quantity of benefits for their items, the number of items purchased is endogenous since it is based on an overall auction budget, not to mention other practical reasons equivalence results often do not apply such as risk aversion and bounded rationality. Our focus is therefore *not* on comparing the outcomes of these auctions to theoretical predictions, but we can, nevertheless, compare the relative empirical performance of the two auction institutions for different environmental management applications. Still, it is useful to have some theoretical benchmarks based on simplifying assumptions to motivate the institutional comparison.

The most reasonable benchmark for the uniform-price auction is full revelation: offer = cost. In this type of "first-rejected-offer" uniform-price auction sellers usually have a dominant strategy to offer their projects at cost. This is because submitting an offer below cost would only increase the probability of acceptance if the price received falls below cost, and submitting an offer above cost is very unlikely to raise the price.[7] For the auction budgets and the actual realized costs and benefits draws employed in the experiment, under full cost revelation these uniform price auction rules extract 72.4% of the maximum possible abatement in the nitrogen reduction environment and 86.6% of the maximum possible abatement in the salinity reduction environment.

Sellers' costs are distributed independently in this laboratory environment, so independent, private-value auction theory for multiple-unit, discriminative-price auctions provides a benchmark approximation in the discriminative-price auction treatment. Since sellers receive the price they offer, they clearly have an incentive to offer prices above costs. How much above costs they should offer depends on the number of sellers in the auction and the number of units accepted by the auctioneer. Our experiments employed $N = 8$ sellers, and the sellers could infer over time from the rate that they successfully sold that typically the auctioneer purchased $Q = 5$ units each period in the nitrogen environment, or $Q = 5$ or $Q = 6$ units each period in the salinity reduction environment.[8] If, as a first approximation, sellers behave *as if* they know Q and that it is stable, and they prepare offers on each of their three units independently, we can estimate how

[7] An offer above cost could occasionally raise price in our setting because sellers' different projects have different environmental benefits and the auction has a monetary budget constraint. It is therefore possible to construct examples in which a seller could raise the offer price on one of her items above cost and have a different (higher environmental benefit) item accepted, which would in turn exclude different rivals' items and raise the uniform cutoff price. Sellers do not observe their projects' environmental benefits, nor do they observe the offers or costs of their rivals; therefore, the incomplete information setting of our experiment—chosen to reflect reasonable incomplete information in any field implementation—makes the identification of this misrepresentation incentive rather implausible.

[8] In the nitrogen reduction environment, exactly $Q = 5$ units were sold in 64% of the periods, and the Q sold was 4, 5, or 6 in 99% of the periods. In the salinity reduction environment, $Q = 4$ in 6.2% of the periods, $Q = 5$ in 42.1% of the periods, and $Q = 6$ in 51.7% of the periods.

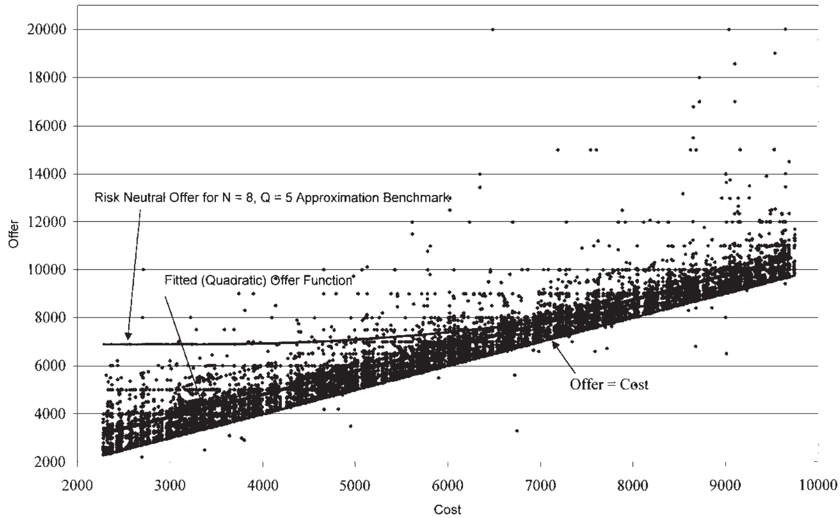


FIGURE 1
ALL INDIVIDUAL OFFERS FOR THE DISCRIMINATIVE-PRICE TREATMENT IN THE NITROGEN REDUCTION ENVIRONMENT

much they will offer above cost based on standard results from Vickrey auctions (see, e.g., Cox, Smith, and Walker, (1984), for the relevant formula). As shown in Figure 1, the equilibrium offer function under these simplifying assumptions is nonlinear and substantially exceeds cost for low-cost draws. For our parameters, the equilibrium offers for the low-range cost draws are two or three times higher than cost based on this approximation. Consequently, for the actual realized cost and benefits draws employed in the experiment, in the nitrogen reduction environment these discriminative price auction rules extract only 54.8% of the maximum possible abatement if this offer function approximation is accurate. The corresponding benchmark for the salinity reduction environment is 63% of the maximum possible abatement for both the $Q = 5$ and $Q = 6$ approximations. These benchmarks are substantially below the benchmark prediction for the uniform price auction (72.4% and 86.6%, respectively, for nitrogen and salinity as noted above), so we expect that uniform-price auction rules will result in more efficient pollution abatement than discriminative-price rules.

III. RESULTS

Figures 1 and 2 present an overview of the offer data for the nitrogen reduction environment.[9] Figure 1 indicates that nearly all offers (99%) exceed cost as expected in the discriminative price auction. Most offers (73%) lie in a band between cost and cost + $1,000, and 45% are within $500 of cost. The offer data for the salinity reduction environment are similar; 99.6% of the offers exceed costs and most offers (89%) lie in a band between cost and cost + $28, and 58% are within $14 of cost.[10] Fig-

[9] This figure, and all the analysis that follows in this section, excludes a small number of offers that were obvious typographical errors. These occurred when sellers accidentally left a digit off of their offer, such as making an offer of 1,030 with a cost of 9,250 in the discriminative price treatment. This seller clearly intended a different offer (such as 10,300) since the offer of 1,030 virtually guarantees her a loss of 8,220, and this occurred in period 35 when this seller had plenty of experience. We excluded a total of 27 such typographical errors, out of 25,896 offers submitted (0.10%). We also lost all 24 offers from one period in one uniform price session due to a data recording error.

[10] Note that the low-cost projects have offers that are much lower relative to the risk neutral benchmark in Figure 1, compared to the high-cost projects. This behavior is analogous to the higher bids, relative to the

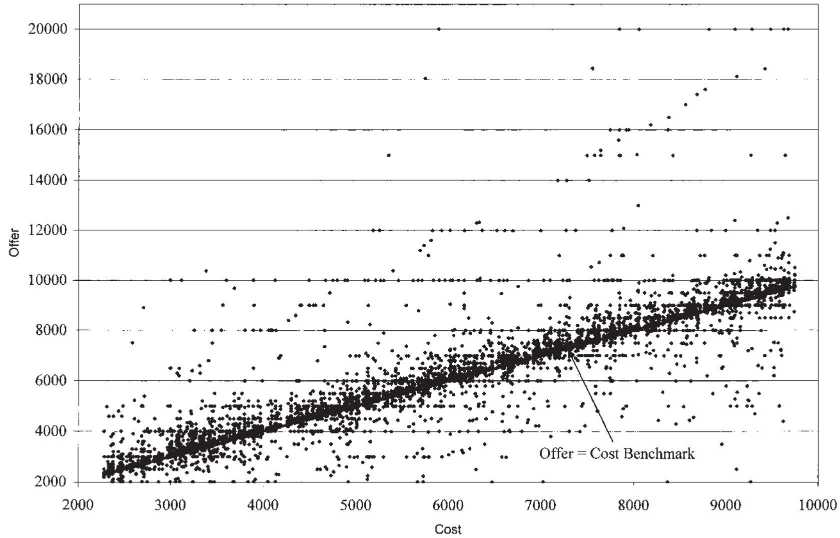


FIGURE 2
All Individual Offers for the Uniform-Price Treatment in the Nitrogen Reduction Environment

ure 2 shows that offers are dramatically different in the uniform price auction. The scatterplot of offers is more centered on the offer = cost reference line (indeed, the offer dots practically obscure this line). While there is some variation in offers relative to costs and nearly two-thirds (64%) of the offers are above cost, 80% of the offers are within $500 of cost. Similarly, for the salinity reduction environment, two-thirds (67%) of the offers are above cost and 85% of the offers are within $14 of cost. In the first subsection, we summarize the impact of the auction rules and these offers on overall market performance, before we return to analyze the offer behavior in more detail in the second subsection.

Overall Market Performance

Following Casan, Gangadharan, and Duke (2003), we compare the auction formats using three market performance measures. These measures differ from the standard allocative efficiency measures typically applied in laboratory auction research. For the auction to be allocatively efficient, it must select the least costly projects. But in this policy application, to improve efficiency the auction also needs to select projects with high environmental benefits (quality). The first market performance measure, called P-MAR (for the *Percentage of Maximum Abatement Realized*), is the amount of pollution abatement realized by the auction mechanism, as a percentage of the highest amount of abatement that could be achieved with the government's auction budget. This maximum is based on the realized cost and benefit draws each period. This maximum abatement target could be achieved, for example, if the government knew both the cost and quality of each project and could implement its selected projects at their cost.[11]

risk neutral equilibrium, for higher value items in the buyer auctions reported in Cox, Roberson, and Walker (1984). Seller risk aversion is one possible explanation for these lower offers for low cost projects.

[11] Sometimes this maximum abatement would occur in the discriminative price auction if all sellers offer their projects in the auction at cost. Cost-revealing seller behavior does not always result in maximum abatement, however. The auction ranks the offers on the basis of their offer/quality ratio, and selects those with the lowest ratios. This greedy algorithm does not always result in the maximum abatement achievable for a fixed budget,

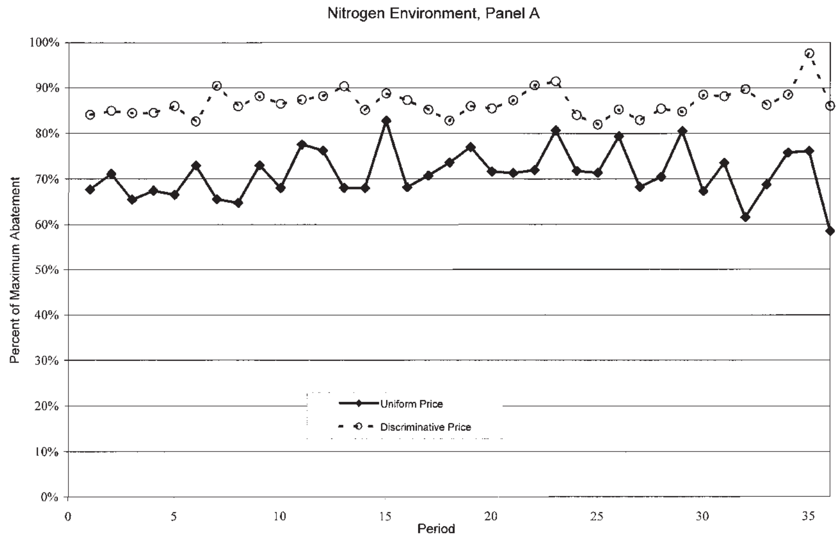
Figure 3 shows that average P-MAR is greater in the discriminative-price auction than in the uniform-price auction in all 36 periods of the nitrogen reduction environment and in 31 of 36 periods in the salinity environment. The left side of Table 3 presents P-MAR averaged across periods, separately for each session. The lowest efficiency across the 10 discriminative-price sessions (80.8%) is greater than the highest efficiency across the 10 uniform-price sessions (74.2%) in the nitrogen reduction environment, so a nonparametric Wilcoxon test based on one (statistically independent) observation per session strongly rejects the hypothesis of equal efficiencies (p-value = 0.0014).[12] Similarly, for the salinity reduction environment, the lowest efficiency across the five discriminative-price sessions (88.3%) is greater than the highest efficiency in the uniform-price sessions (85.4%) so the Wilcoxon test rejects the hypothesis of equal efficiencies (p-value = 0.03).

The regression shown in the first column of Table 4 presents additional parametric evidence to determine whether the conclusions are robust when controlling for other factors such as experience (time period) and subject pool. These panel regressions are based on a random-effects error structure, with the session representing the random effect, in order to account for the correlation of market outcomes within a session. We include a dummy variable for the experiment site to account for any cultural or demographic differences across subjects, but this term is not significant in any Table 4 regression. We also include *ln(period)* to allow the model to capture differences in performance across periods, and the time trend is statistically significant in all cases. The negative and highly significant estimate on the uniform price treatment dummy variable indicates that P-MAR efficiency is about 15% lower in the uniform-price auction than in the discriminative-price auction in the nitrogen reduction environment. The difference between the pricing rules leads to a smaller difference in performance for the salinity reduction environment, but the pricing rule is still statistically highly significant. Although Figure 3 does not indicate any pronounced trend over time, the positive and significant *ln(period)* term indicates that performance improves modestly across periods in both environments. In addition to the results reported in Table 4, we conducted regressions with alternative specifications for P-MAR. P-MAR is an efficiency measure that cannot exceed 100% by definition. We estimated a random-effects tobit model to account for the censoring at 100%, but the results from that model are identical to the results reported in Table 4. This is because only 7 out of 694 of the observations in the nitrogen treatment are actually censored and none of the observations in the salt treatment are censored. We therefore do not present these tobit results in Table 4.

The second market performance measure provides an alternative summary of the auctions' ability to obtain the most abatement for the auction budget. We use P-OCER (for the *Percentage of Optimal Cost-Effectiveness Realized*) to refer to the actual quantity of abatement per dollar spent in the auction, as a percentage of the quantity of abatement per dollar spent in the "maximal abatement" solution to this problem described above. It differs from

due to the discrete set of projects acceptable in any auction period. Some higher abatement projects could be excluded from the auction allocation due to a cost that exceeds the fixed budget, while higher offer/quality ranking projects are accepted because of their lower overall cost. Consequently, some rearrangement of the selected projects can sometimes modestly increase the total abatement realized. To determine the selected projects that maximize pollution abatement, we calculated the total abatement for the 4^8 = 65,536 possible project combinations each period, and determined the greatest abatement among all the affordable project combinations. If all sellers offered their projects at cost, then the discriminative price auction selects the combination of projects that maximize abatement in 12 of the 36 periods in the nitrogen reduction environment and in 6 of the 36 periods in the salinity reduction environment. In 28 of the 36 periods for the nitrogen environment and in 19 of the 36 periods for the salinity environment, full cost revelation achieves at least 95% of the maximum possible abatement.

[12] Wilcoxon's test is based on comparing all pairs of observations by summing the ranks of the observations in the two samples (e.g., see Siegel 1988). The null hypothesis tested here is that the uniform and the discriminative price treatments achieve equal efficiency levels.



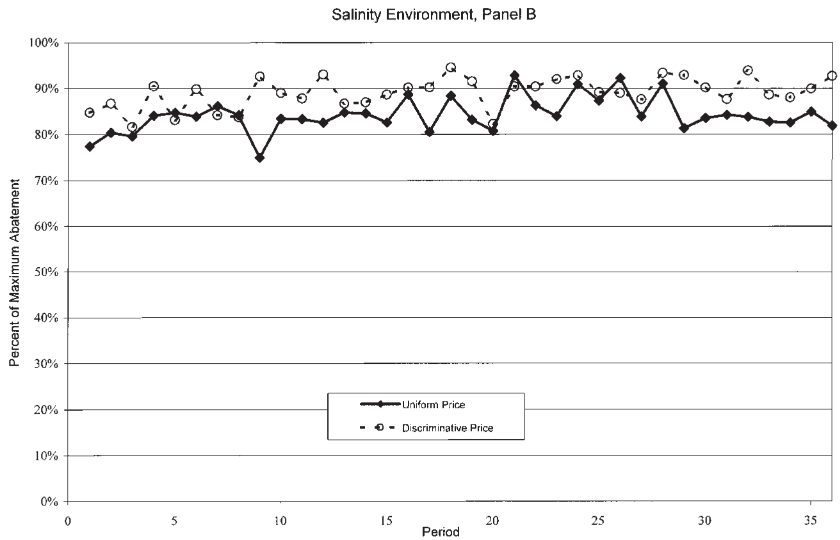


FIGURE 3
Percentage of Maximum Abatement Realized, by Treatment for Each Period Nitrogen Environment Panel A; Salinity Environment Panel B

P-MAR because different amounts are spent in this auction since the auction selects a discrete set of projects. Presumably the unspent resources have some alternative value, so a reasonable objective is to maximize the abatement per dollar.

Figure 4 and the middle of Table 3 show that P-OCER, like P-MAR, is uniformly higher in the discriminative-price auction than in the uniform-price auction (Wilcoxon p-value = 0.0014 in the nitrogen reduction environment and 0.03 in the salt reduction environment). The regression in the second column of Table 4 indicates that P-OCER efficiency is on average about 11% higher in the discriminative-price auction in the nitrogen reduction environment and 3% higher in the salinity reduction environment.

TABLE 3
OVERALL PERFORMANCE BY SESSION

	Average P-MAR		Average P-OCER		Average Seller Profits	
	Discriminative Price	Uniform Price	Discriminative Price	Uniform Price	Discriminative Price	Uniform Price
Nitrogen Reduction Environment						
Ten individual sessions in each treatment	82.8%	69.4%	86.5%	81.6%	4722	6723
	85.2%	72.6%	90.3%	82.1%	3923	6682
	84.3%	72.4%	88.6%	83.1%	4383	6528
	80.8%	74.2%	86.9%	84.9%	4840	5467
	88.6%	69.6%	94.6%	77.4%	2501	7828
	90.7%	70.4%	97.0%	79.9%	2108	7242
	88.8%	71.1%	95.5%	80.8%	2387	6593
	88.8%	71.7%	94.6%	80.5%	2555	6962
	88.4%	73.4%	94.4%	82.8%	2527	6098
	88.4%	67.2%	94.4%	80.2%	2932	5952
Treatment Mean	86.7%	71.2%	92.3%	81.3%	3288	6608
Salt Reduction Environment						
Five individuals in each treatment	89.0%	84.6%	94.8%	91.3%	59.4	95.6
	89.5%	85.4%	94.3%	92.7%	68.7	78.2
	89.4%	83.2%	94.4%	90.2%	67.9	107.1
	89.1%	83.1%	94.4%	91.7%	62.0	88.5
	88.3%	84.7%	94.4%	91.2%	60.5	96.2
Treatment mean	89.1%	84.2%	94.5%	91.4%	63.7	93.1

The positive and significant *ln(period)* term indicates that like P-MAR, P-OCER increases across time.[13]

The third performance measure is seller profits. Seller profits represent money "left on the table" that the government "overspends," relative to the actual cost of implementing the land use changes. Therefore, lower seller profits are better from the government's perspective.

Figure 5 shows that sellers almost always earn higher profits on average in the uniform-price auction, and in some periods their earnings are dramatically higher—even double the profits of the discriminative-price auction. The right side of Table 3 shows that similar to the efficiency calculations, in the nitrogen reduction environment the highest average seller profits in the discriminative price auction (4,840) are smaller than the lowest seller profits in the uniform-price auction (5,467), so the Wilcoxon test also strongly rejects the hypothesis of equal seller profits across auction treatments (p-value = 0.0014). Similarly for the salinity reduction environment, the highest average seller profits in the discriminative-price auction (68.7) are smaller than the lowest seller profits in the uniform-price auction (78.2) and the Wilcoxon test rejects the hypothesis of equal seller profits across treatments (p-value = 0.03). The seller profits regression model in the third column of Table 4 also mirrors those of the abatement efficiency models. Seller profits are significantly higher in the uniform price auction, by over 3,000 experimental dollars, per period, on average in the nitro-

[13] We do not use a tobit model for the P-OCER regressions because this measure can—and occasionally does—exceed 100%. This occurs when the auction does not purchase the maximum achievable benefit given the auction budget, but it expends considerably less than the total budget so that the abatement per dollar exceeds the abatement per dollar at the maximal abatement solution.

TABLE 4
REGRESSION MODELS FOR MARKET PERFORMANCE MEASURES

Variable	Percentage of Maximum Abatement Realized (P-MAR)	Percentage of Optimal Cost Effectiveness Realized (P-OCER)	Seller Profits
	Nitrogen Reduction Environment		
Intercept	0.83*** (0.01)	0.89*** (0.01)	4785.6*** (407.9)
Dummy = 1 if uniform-price treatment	−0.15*** (0.01)	−0.11*** (0.01)	3307.1*** (386.91)
Dummy = 1 if site = Melbourne	0.01 (0.01)	0.02 (0.01)	−645.2 (386.92)
Ln(period)	0.01*** (0.002)	0.01*** (0.003)	−437.0*** (86.95)
Observations	694	694	694
	0.57	0.38	0.41
	Salt Reduction Environment		
Intercept	0.84*** (0.009)	0.90*** (0.006)	101.8*** (6.79)
Dummy = 1 if uniform-price treatment	−0.05*** (0.005)	−0.03*** (0.004)	28.8*** (5.67)
Dummy = 1 if site = Melbourne	−0.01 (0.005)	−0.006 (0.004)	3.2 (5.67)
Ln(period)	0.02*** (0.003)	0.02*** (0.002)	−14.8*** (1.89)
Observations	358	358	358
R^2	0.26	0.37	0.28

Notes: Standard errors are in parentheses. All models are estimated with a random-effects error structure, with the session as the random effect. For the P-MAR model for salt reduction, the random-effects model and the OLS regression give identical estimates, because the error term representing the random session effects has a coefficient of zero, implying that a random-effects model is not required in that sample. We hence report OLS estimates for this model.

*** Denotes a coefficient that is significantly different from zero at 1%.

gen reduction environment and by nearly 29 experimental dollars in the salinity reduction environment. These average differences in profits across auction institutions represent approximately 80% and 20% of the cost of the median accepted offer in the nitrogen and the salinity reduction environments, respectively. Overall, the results in Figures 3 through 5 and Tables 3 and 4 indicate that market performance is lower in the uniform-price auction.

Offer Behavior

In this section we examine the individual offers made by sellers by estimating empirical offer functions that relate offers to cost draws. First, however, recall that our design employed the same set of cost draws across all 20 sessions in the nitrogen reduction environment and across all 10 sessions in the salinity reduction environment that is, we use the same set of 8 sellers × 3 items × 36 periods = 864 cost draws in each session, with separate draws of course for the nitrogen and salinity environments. Thus, we can pair the same cost draws for each of the 10 pairs of sessions in the nitrogen reduction environment and in each of the 5 pairs of sessions in the salinity reduction application and compare the corresponding offers across auction treatments. This simple and direct comparison between the offers indicates that offers are on average 572 experimental dollars higher in the discriminative-price session (standard error of the mean = 43) for the nitrogen reduction environment and 14.3 experimental dollars higher in the discriminative-price session (standard error of the mean = 0.59) for the salinity reduction environment. The average number of units bought by the regulator in the uniform-price sessions is lower than in the discriminative-price sessions, but the difference is statistically significant only for the nitrogen reduction environ-

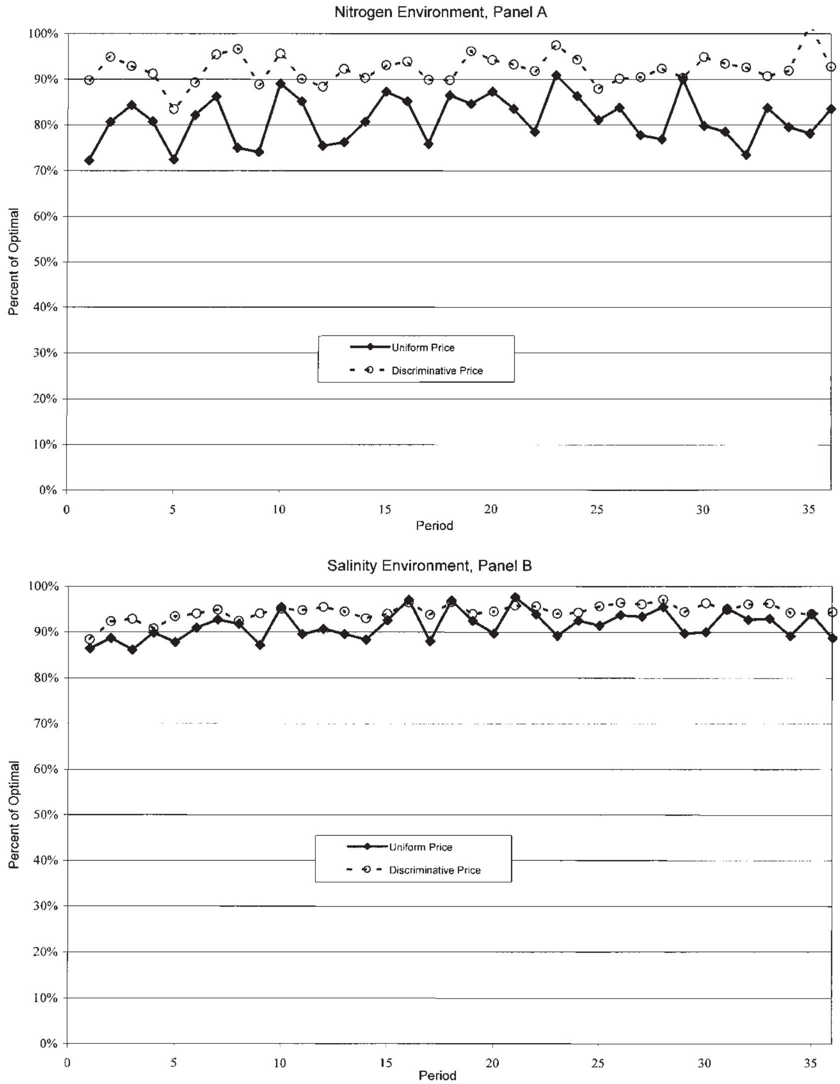


FIGURE 4
PERCENTAGE OF OPTIMAL COST-EFFECTIVENESS REALIZED, BY TREATMENT FOR EACH PERIOD. NITROGEN ENVIRONMENT PANEL A; SALINITY ENVIRONMENT PANEL B

ment. The median variance of offers is also higher in the uniform price sessions, however the difference is not statistically significant in either environment.

Table 5 presents random effects regressions of seller offer functions separately for the two auction treatments. Columns 1 and 2 report the results for the discriminative-price treatment and column 3 presents the estimates for the uniform-price treatment. The dependent variable is the seller's offer price, and the explanatory variables include costs faced by sellers for the different projects, a dummy variable for the site of the experiment, and time (the natural logarithm of the period number). We report both linear and nonlinear specifications for the discriminative price

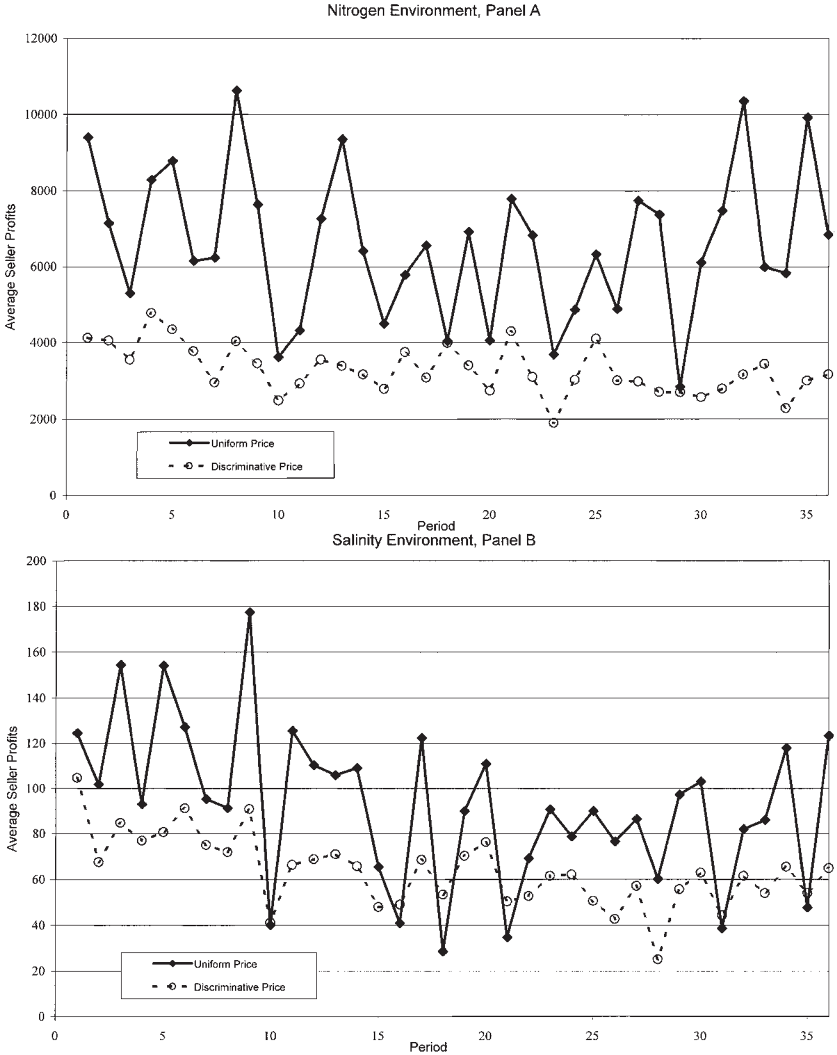


FIGURE 5
AVERAGE SELLER PROFITS, BY TREATMENT FOR EACH PERIOD.
NITROGEN ENVIRONMENT PANEL A; SALINITY ENVIRONMENT PANEL B

treatment, since the theoretical approximation in Figure 1 suggests a nonlinear specification for this institution.[14] Note, however, that the nonlinear term (costs^2) is not significantly different from zero for either environment.

The results show that there is a strong positive relationship between the project cost and the offers in both the uniform-price auction and the discriminative-price auction. In fact, the coefficient on the cost variable is not significantly different from one, for either auction format in either en-

[14] In particular, the theoretical approximation shown in Figure 1 for the nitrogen reduction environment is fit very accurately with the quadratic specification Offer = 7573 − 0.429Cost + 0.000067Cost^2.

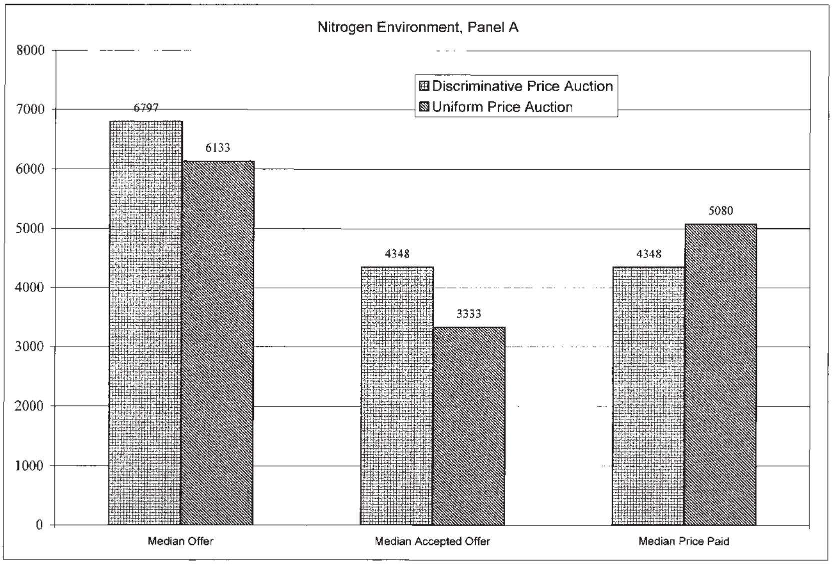
TABLE 5
Seller Offer Function Estimates

Variable	Discriminative Price Treatment (1)	Discriminative Price Treatment (2)	Uniform Price Treatment (3)
Nitrogen Reduction Environment			
Intercept	1,399.87*** (106.83)	1,626.03*** (182.67)	278.25 (234.13)
Costs	0.99*** (0.009)	0.90*** (0.057)	1.03*** (0.017)
Costs^2	–	0.0000070 (0.0000046)	–
Dummy = 1 if site = Melbourne	−312.49*** (99.69)	−312.44*** (99.42)	330.33 (254.81)
Ln(period)	−142.06*** (22.41)	−142.09*** (22.41)	−157.37*** (41.70)
R^2	0.58	0.58	0.29
Number of observations	8,621	8,621	8,610
Salt Reduction Environment			
Intercept	31.65*** (2.34)	29.53*** (6.29)	16.84*** (3.74)
Costs	1.02*** (0.006)	1.04*** (0.064)	0.99*** (0.009)
Costs^2	–	−0.000059 (0.00016)	–
Dummy = 1 if site = Melbourne	2.55 (2.84)	2.55 (2.67)	5.59 (3.65)
Ln(period)	−7.02*** (0.35)	−7.03*** (0.35)	−6.12*** (0.57)
R^2	0.86	0.86	0.70
Number of observations	4,318	4,318	4,317

Notes: Standard errors are in parentheses. All models are estimated with a random-effects error structure, with the subject as the random effect.
*** Denotes a coefficient that is significantly different from zero at 1%.

vironment, indicating a similar one-to-one relationship between costs and offers in both treatments. These estimated offer functions instead differ in their intercepts. In the nitrogen reduction environment, the intercept in the uniform-price auction is not significantly different from zero, so combined with the cost coefficient not different from one these estimates support the conclusion that sellers on average made offers equal to cost. That is, sellers' behavior, on average, is consistent with the revelation incentives for this auction institution discussed at the end of Section 2. By contrast, the intercept in the discriminative price auction is significantly greater than zero. The estimate indicates that offers were on average at least 1,000 experimental dollars above cost. or the salinity reduction environment, the offer function intercept is significantly positive for both uniform-price and discriminatory-price sessions. However, offers increase over time in the discriminatory-sessions, while they decline over time in the uniform price sessions. In the uniform-price treatment this substantial time trend cancels out the positive intercept by period 16.

Figure 1 displays a quadratic offer function fit through all the offers in the discriminatory price treatment, and it shows that on average the relationship between offers and costs is approximately linear. More important, this figure illustrates that sellers of low-cost projects in this incomplete information environment did not overstate their costs when submitting offers nearly as much as predicted by our benchmark approximation indicated on the figure. These low-cost projects are particularly important for the overall efficiency and abatement realized in the auction, since they are most likely to be accepted by the auctioneer. Sellers offered these projects at prices closer to costs than we predicted, which is why the discriminative-auction performed better than the uniform-price auction.



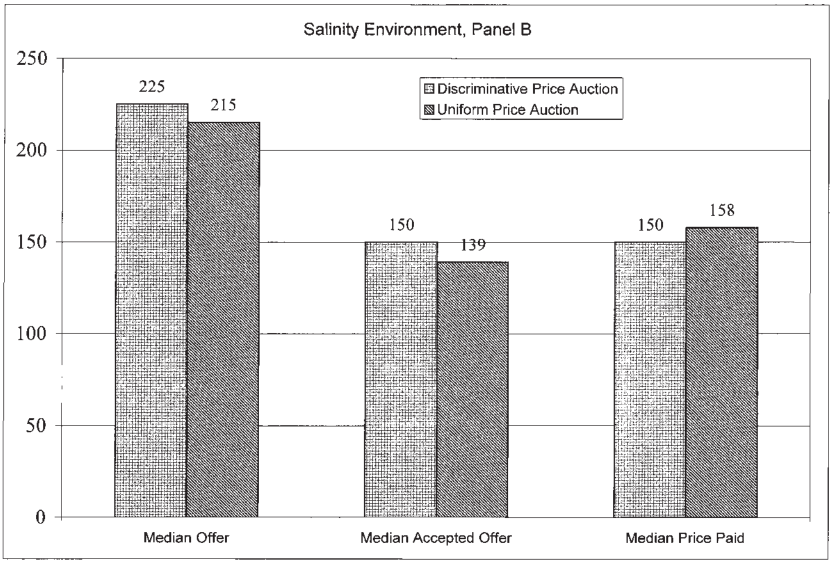


FIGURE 6
MEDIAN OFFERS AND PRICES PAID. NITROGEN ENVIRONMENT PANEL A, SALINITY ENVIRONMENT PANEL B

The other reason for the performance difference is that the quantity of projects accepted in the two auctions is significantly different. Figure 6 shows that the median prices paid per project are higher in the uniform-price treatment than in the discriminative-price treatment, even though the median offers submitted by the sellers and the median accepted offers are lower in the uniform-price sessions. This implies that the buyer operating with a fixed budget can buy more environmental projects on average in the discriminative-price auction and this, in turn, leads to lower efficiency in the uniform price sessions. For example, in the nitrogen reduction environment 4.15 projects were bought on average in each uniform-price auction, compared to 5.06 projects on average in each discriminative-price auction.[15]

IV. DISCUSSION

Auctions allow an environmental regulator and landholders to use information about environmental benefits and land use management costs to help protect the environment. The auctions examined here suggest how an environmental agency can use public resources to subsidize land use changes that aim to reduce pollution. It is important therefore to ensure that the agency's environmental budget is well spent, and this is where the details for the actual design of the auction become critical.

The laboratory auctions reported in this paper compare uniform-price allocation rules with discriminative-price rules. The experiment makes this comparison in two different environmental applications—nitrogen reduction and salinity reduction. The offer function estimates indicate that offers were not significantly different from costs in the uniform-price treatment, so seller subjects on average made offers in this auction format that were consistent with the cost-revelation incentives of this institution. Nevertheless, this auction format does not achieve full efficiency, since the uniform price was set by the first rejected seller's offer, and all successful sellers received this price per unit of quality. Since successful sellers receive prices that exceed their offers and offers were approximately equal to costs, prices exceed costs and some inefficiency occurred.

The offer function estimates indicate that offers substantially exceed costs in the discriminative-price treatment, and that each increase in costs by one dollar is matched with an increase in the offer by one dollar. Prices are set equal to offers, so submitting offers above costs is the only way that sellers can earn positive profits in this auction institution. This auction is also not fully efficient, but the results indicate that the inefficiency and the amount sellers are "overpaid" relative to their project costs are lower in the discriminative-price auction than the uniform-price auction. This occurred because sellers did not "mark up" offers above cost as much as suggested by an approximation based on multi-unit, discriminative-auction theory. In addition, the first rejected seller rule for setting the price in the uniform-price auction leads to higher prices paid per project than in the discriminative-price sessions, which in turn reduces the number of projects the buyer can obtain in the uniform-price auction. This has an impact on reducing efficiency in the uniform-price sessions.

It is important to emphasize that these conclusions are based on particular parameterizations of project costs, land uses, and potential environmental benefits. We chose these parameters carefully to approximate the conditions for two specific environmental problems being considered for land use change auctions, but these conclusions may not hold in other situations. For example, intuition from auction theory suggests that the degree to which sellers submit offers above cost in the discriminative-price auction should depend on the number of sellers (N) relative to the number of items purchased (Q). Therefore, it is important to determine whether the ordering clearly established in this initial experiment continues to hold in other settings that approximate non-point source pollution in other regions and land uses.

The experiment reported in this paper also abstracts away from enforcement and

[15] The site dummy is negative and significant for the discriminative price treatment in Table 5. Seller offers are significantly lower in this treatment in Melbourne compared to Purdue. Subjects were mostly undergraduate economics and business students at both sites, who had never before participated in laboratory sealed-offer auctions. The Purdue subjects, however, were generally more experienced in experiments because many were recruited online through a database of subjects that had participated in other economics experiments. The rate of obvious mistakes, such as offers below cost, was quite low in both samples, but perhaps because of their greater experience the obvious mistake rate was lower at Purdue (0.48%) than at Melbourne (0.73%). This might be one explanation for this small difference in behavior across sites.

monitoring problems. Field implementation of the land use auctions would require an examination of these monitoring issues to enable the auction mechanism to obtain the maximum environmental and economic benefits. We should also emphasize that these laboratory testbed experiments represent only the first step in the long process from auction design to field implementation. For example, it will be useful to conduct experiments with actual landowners, using the environmental terminology—and the relevant value judgments that environmental protection and property rights evoke in this more relevant population. The preferred auction design can then be evaluated in small-scale field experiments with landholders, implementing actual land use changes. The results reported here suggest that uniform price auction rules may not perform better than discriminative price rules, even though they have better cost-revelation incentives.

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