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# A LABORATORY COMPARISON OF UNIFORM AND DISCRIMINATIVE PRICE AUCTIONS FOR REDUCING NON-POINT SOURCE POLLUTION

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

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## Abstract

Land use changes to reduce non-point source pollution, such as nutrient runoff to waterways from agricultural production, incur opportunity costs that are privately known to landholders. Auctions may permit the regulator to identify those management changes that have greater environmental benefit and lower opportunity cost. This paper reports a testbed laboratory experiment in which landowner/sellers compete in sealed-offer auctions to obtain part of a fixed budget allocated by the regulator to subsidize pollution abatement. One treatment employs uniform price auction rules in which the price is set at the lowest price per unit of environmental benefits submitted by a seller who had all of her offers rejected. Another treatment employs discriminative price rules in which successful sellers receive their offer price. Our results indicate that subjects recognize the cost-revelation incentives of the uniform price auction, as a majority of offers are within 2 percent of cost. By contrast, a majority of offers in the discriminative price auction are at least 8 percent greater than cost. Nevertheless, the regulator spends more per unit of environmental benefit in the uniform price auction, and the discriminative price auction has superior overall market performance.

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Key Words: Uniform Price Auctions, Discriminative Price Auctions, Land Use Change, Laboratory Experiments, Environmental Policy.

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## 1. 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 like 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 mitigate 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 "environmental procurement:" uniform price auctions and discriminative price auctions. Landowners offer projects that generate environmental improvement in these auctions. More specifically, sellers offer projects with different costs and different levels of environmental benefits to the regulator, who is the buyer and ranks the offers on the basis of their offer price and the potential 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. All participants submit sealed offers, and in the uniform price auction the successful sellers receive a uniform price (per unit of environmental benefit) equal to the lowest rejected offer. In the discriminative price auction, each successful seller receives 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 equals 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 receive a market-clearing price that exceeds their offer and 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 these types 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, 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 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 et al. (1985) find that subjects failed to follow their dominant strategy of bidding equal to values in multiple unit, uniform price, sealed bid auctions. Cox et al. (1982) and Kagel et al. (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

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[1] For example, Holt (1980) shows that for risk averse buyers, the discriminative auction results in higher expected revenue, and Maskin and Riley (2000) relax the assumption of symmetry and assume that the buyers' reservation values are not identically distributed. In this case the revenue equivalence theorem does not hold and the ranking of different auctions would depend on how the distributions vary across buyers. Some researchers have argued that the uniform price auction has a lower winner's curse in common value environments and results in greater revenue to the seller than would a discriminative auction (see Milgrom, 1989; Bikhchandani and Huang, 1993). However this work was based on a single-unit auction theory and Back and Zender (1993) show that this result is critically dependent on the assumption that the good was indivisible.

the assumptions for the revenue equivalence theorem. For example, the auctions studied here assume that sellers offer multiple projects for sale, but because of the interaction of the environmental benefits across projects the regulator would choose at most one project from each seller.[2] In this setting, sellers may not make optimal offers independently on 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 regulator 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. Moreover, the fixed budget constraint for the regulator 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

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[2] For example, the installation of grassed swale drains with sediment traps to reduce nutrient loads would reduce the environmental benefit of decreased fertilizer applications. The benefits of these two alternative mitigation strategies are therefore interrelated, but the benefits would be evaluated separately in the auction for simplicity. To avoid the complication of project interactions we limit each seller to supply at most one project.

performance, even though the discriminative auction rules lead to higher offer prices. The empirical research issues examined in this paper are crucial to understand better 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 like 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.

## 2. Experimental Design

### 2.1 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 percent of the land) and contributes to 53 percent 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 quality 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 the costs of their land use change projects, but they do not know the associated quality (environmental benefit). We do not reveal the environmental benefits to sellers 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. In order to enhance the external validity of the experiment, we also do not provide sellers with any information about other sellers' costs and quality or the distributions that are used to generate the costs and qualities. They are told simply that the costs and quality levels would be different across sellers and could change from period to period. They also do not know the regulator's budget, which is fixed at $25,000 experimental dollars per period in the nitrogen reduction environment and $1000 experimental dollars per period in the salt reduction environment.

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[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).

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.

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 format and 7 in the discriminative price format) and 15 conducted at Purdue (7 in the uniform price format and 8 in the discriminative price format). All sessions have 36 trading periods. In each session eight seller subjects offer items in a computerized sealed offer auction, so across all 30 sessions a total of 240 different subjects participated. 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 below for a specific example. Once the allocation is made the results are reported to the subjects electronically on their web browser.

As is usual in experimental economics, we use neutral terminology in the instructions to refer to the different items that sellers could offer. The appendix contains the experiment instructions. 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 1000 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.

### 2.2 Treatments and Predictions

Our goal in this experiment is to compare the performance characteristics of uniform price 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 that (2) total expenditures do not exceed the overall auction budget.[4]

Table 2 presents an example from period 31 in two sessions to illustrate the rules. In both auction formats the algorithm first calculates ratio of the offer price to the environmental 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

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[4] 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.

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 2999, 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 environmental 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.[5] For the auction budgets and the

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[5] 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

actual realized costs and environmental benefits draws employed in the experiment, under full cost revelation these uniform price auction rules extract 72.4 percent of the maximum possible abatement in the nitrogen reduction environment and 86.6 percent 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.[6] 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 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 below 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 environmental benefits draws employed in the experiment, in the nitrogen reduction environment these discriminative price auction rules extract only 54.8 percent

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incomplete information in any field implementation—makes the identification of this misrepresentation incentive rather implausible.

[6] In the nitrogen reduction environment, exactly $Q$=5 units were sold in 64 percent of the periods, and the $Q$ sold was 4, 5 or 6 in 99 percent 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.

of the maximum possible abatement if this offer function approximation is accurate. The corresponding benchmark for the salinity reduction environment is 63 percent 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 percent and 86.6 percent 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.

## 3. Results

Figures 1 and 2 present an overview of the offer data for the nitrogen reduction environment.[7] 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+$1000, 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. Figure 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, nearly two thirds (67%) of the offers are above cost and 85% of the offers are within $14 of cost. In the first subsection we

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[7] 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.

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 Subsection 3.2.

### 3.1 Overall Market Performance

Following Cason et al. (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.[8]

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

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[8] 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, 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 percent of the maximum possible abatement.

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). Similarly for the salinity reduction environment, the lowest efficiency across the 5 discriminative price sessions (88.3%) is greater than the highest efficiency in the uniform price treatment (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 that controls 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. We also include ln(period) to allow the model to capture differences in performance across periods. The negative and highly significant estimate on the uniform price treatment dummy variable indicates that P-MAR efficiency is about 15 percentage points 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.

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 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 percentage points higher in the discriminative price auction in the nitrogen reduction environment and 3 percentage points higher in the salinity reduction environment. The positive and significant ln(period) term indicates that like P-MAR, P-OCER increases across time.

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 (4840) is less than the lowest seller profits in the uniform price auction (5467), 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) is less 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 nitrogen reduction environment and by nearly 29 experimental dollars in the salinity reduction environment. These average differences in profits across auction institutions represent approximately 80 percent and 20 percent 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.

### 3.2 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 i.e., 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 environment. 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 treatment, since the theoretical approximation in Figure 1 suggests a nonlinear specification for this institution.[9] Note, however, that the nonlinear term ($\text{costs}^2$) 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 and discriminative price treatments. In fact, the coefficient on the cost variable is not significantly different from one for either auction format in either environment, 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

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[9] In particular, the theoretical approximation shown in Figure 1 for the nitrogen reduction environment is fit very accurately with the quadratic specification $\text{Offer} = 7573 - 0.429\text{Cost} + 0.000067\text{Cost}^2$.

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. For the salinity reduction environment, the offer function intercept is significantly positive for both uniform and discriminatory price sessions; however, offers increase over time in the discriminatory price 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 importantly, 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 price auction performed better than the uniform price auction.

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.

## 4. Discussion

Auctions allow an environmental regulator and landholders to use information about environmental benefits and land use management costs to help protect the environment. In the auctions testbedded here the agency uses 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 sellers 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 is 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 environmental regulator can buy 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. 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 landholders, using the environmental terminology—and the relevant value judgments that environmental protection and property rights evoke in this 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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## Appendix: Instructions for Uniform Price Auction Treatment (Discriminative Price Auction instructions are similar)

### General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of ______ Experimental Dollars = 1 real Dollar. The important thing to remember is that the more experimental dollars you earn, the more real dollars that you take home at the end of the experiment.

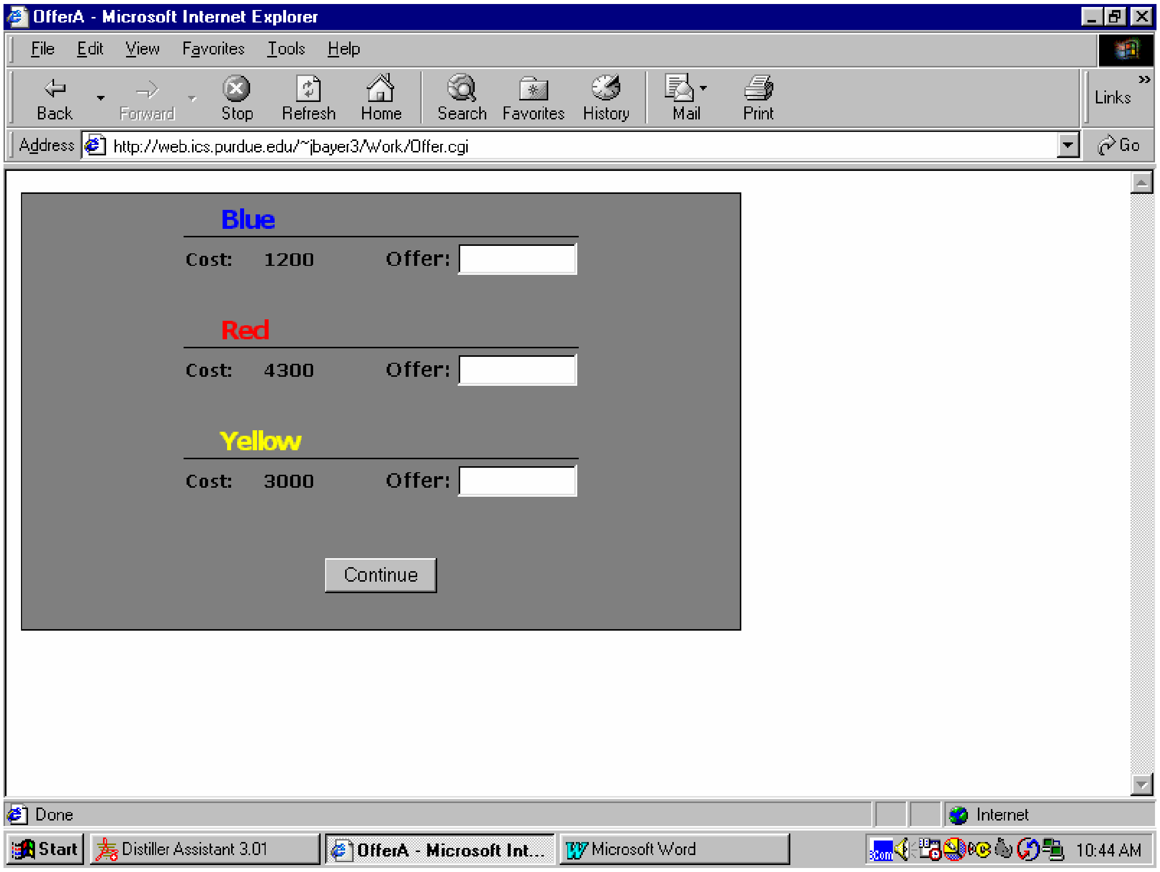
We are going to conduct a set of auctions in which you will be a seller in a sequence of periods. During each auction period you will sell up to one item. You have up to three types of items to sell, called Blue, Red and Yellow items. These items have different levels of "quality" that are valued differently by the experimenter, who is the buyer. Your quality levels may change from period to period, and they may be different from the quality levels of other participants. You can sell only one item per period, and if you sell that item then you must pay that item's cost. If you do not sell any item in a period then your earnings are zero for that period. Notice that you do not pay an item's cost unless you sell that item. Your costs may also change from period to period, and they may be different from the costs of other participants.

Your costs for each of the three types of items are displayed on your computer screen each period, as shown in the example figure on the next page. The profits from sales (which are yours to keep) are computed by taking the difference between the sale price of an item and the cost of that item. (How price is determined will be explained shortly.) That is, [your earnings = (sale price of item) – (cost of item)].

Suppose, for example, that the cost for your Blue item is 110. If you sell your Blue item at a price of 160, your earnings are:

Earnings = 160 – 110 = 50

Notice that if you sell an item for a price that is less than its cost, then you lose money on that sale.



**Blue**

Cost: 1200 Offer:

**Red**

Cost: 4300 Offer:

**Yellow**

Cost: 3000 Offer:

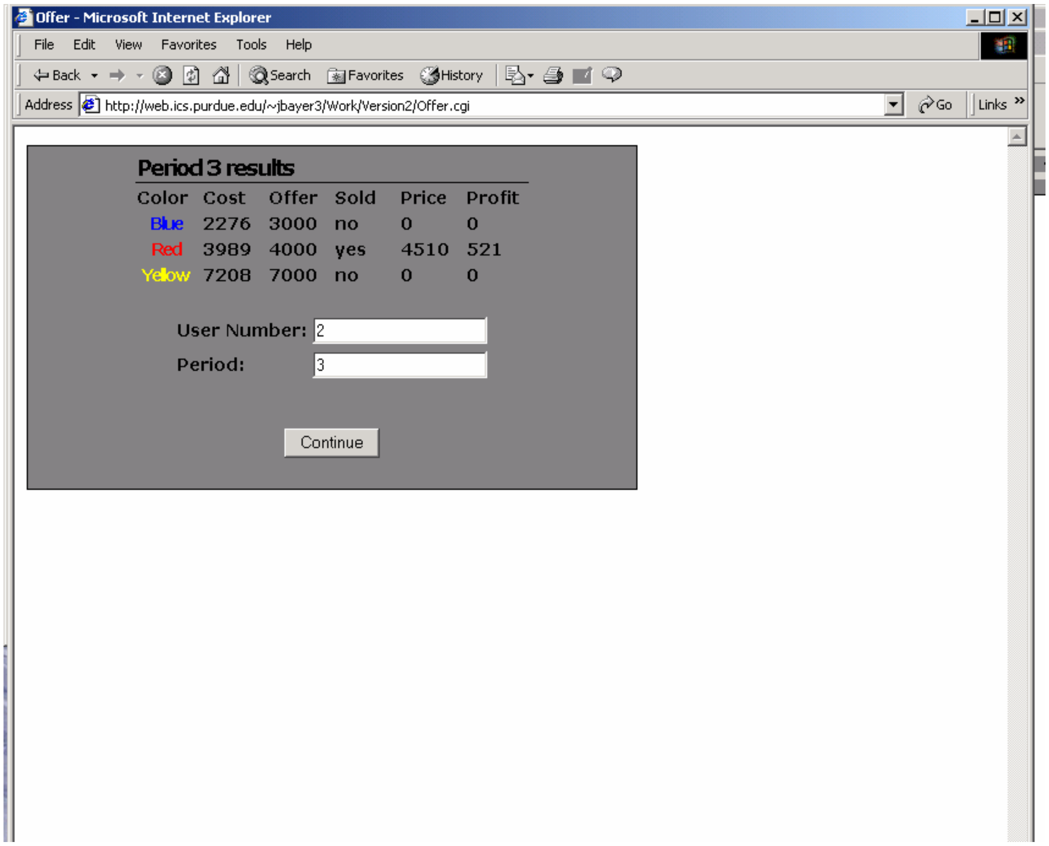
### How Your Price is Determined

The price you receive if you sell an item and which (if any) item you sell is determined using a “sealed offer” auction. In each period you submit an “offer sheet” through your web browser, which lists the minimum amount that you wish to receive for each item. [Do not use a dollar sign when entering your offers on your web browser.] If you sell an item, you will receive a price that is greater than or equal to the price you indicated on your offer sheet for that item.

After everyone submits their offer sheets, the experimenter's computer then ranks the offers on the basis of the offer price and the quality of the items. The experimenter purchases the lowest priced items per unit of quality, spending all of the fixed and constant (and unknown to you) "budget" that is available in the auction. (In the case of a "tie," where two or more items are offered at the same per-quality-unit price but the experimenter cannot purchase them all, the computer randomly determines which item or items are purchased.) Sometimes you may sell an item that you offer at a higher price than some other item when that item has a higher quality. Sometimes you may not sell any item. Remember, the experimenter will buy no more than one item from each seller.

The price you receive if you sell an item is NOT determined by any of the offers you submit. Instead, everyone who sells an item in a period receives the same price per unit of quality, and this price is set by the lowest price per unit of quality submitted by a seller who had all of his or her offers REJECTED. Thus, your profit is not decreased by submitting offers lower than the lowest rejected offer that determines the price. The lower your offers the more likely you will have an offer below the lowest rejected offer and therefore make a successful sale.

In other words, by submitting lower offers you increase the likelihood that you make a sale, but lower offers do not directly reduce the price you receive since the price you receive is determined by a different (rejected) seller's offer. As long as you make offers that are no lower than your items' costs, you have no chance of losing money because if you sell an item you receive a price that is at least as high as your offer price. But if you make offers that are lower than your costs you run the risk of selling at a price less than your cost. This is because the lowest rejected offer could then also be less than your cost and result in a price for you that is less than your cost.



Address: http://web.ics.purdue.edu/~jbayer3/Work/Version2/Offer.cgi

**Period 3 results**

| Color | Cost | Offer | Sold | Price | Profit |
|---|---|---|---|---|---|
| Blue | 2276 | 3000 | no | 0 | 0 |
| Red | 3989 | 4000 | yes | 4510 | 521 |
| Yellow | 7208 | 7000 | no | 0 | 0 |

User Number: 2

Period: 3

After each auction period, the experimenter will tell you when to click the "Continue" button to display the auction results. An example results screen is shown above. It indicates which (if any) item you sell by a "yes" in the Sold column. The results screen also displays the price you receive and the profit on the sale. Circle the color of the one item (if any) that is accepted in the column (1) of your Personal Record Sheet. Then enter the cost of this item, your offer price, the price you receive for the item, and your profit in the other columns of the record sheet. Use a calculator to keep track of your total (cumulative) Experimental Dollar earnings in the rightmost column (6) of your Record Sheet. The results page will automatically increment the period number by 1 for the next period, so after you write down your results on your Record Sheet you should simply press Continue to move to the next period.

**Summary**

- Seller earnings on a sold item = sale price of item – cost of item
- Sellers have three types of items, which can have different costs and quality levels valued differently by the experimenter (who is the buyer). Your costs are shown on your computer screen each period.
- Costs and quality levels may change from period to period and vary across sellers.
- Sellers submit offer prices for three types of items, but the experimenter will buy no more than one item from each seller.
- The experimenter purchases the lowest price items per unit of quality, and spends a constant budget in every auction.
- If you sell an item the price you receive is determined by the lowest price per unit of quality offered by a seller who has all of his or her offers rejected in the auction.

Are there any questions now before we begin the experiment?

**Personal Record Sheet for User Number ____________**

| Period Number | Circle Color Sold (if any) (column 1) | Cost of Sold Item (column 2) | Offer Price for Sold Item (column 3) | Price Received for Sold Item (column 4) | Profit this Period (col. 4 – col. 2) (column 5) | Cumulative Profit (all Periods) (column 6) |
|---|---|---|---|---|---|---|
| 1 | Blue Red<br>Yellow None | | | | | |
| 2 | Blue Red<br>Yellow None | | | | | |
| 3 | Blue Red<br>Yellow None | | | | | |
| 4 | Blue Red<br>Yellow None | | | | | |
| 5 | Blue Red<br>Yellow None | | | | | |
| 6 | Blue Red<br>Yellow None | | | | | |
| 7 | Blue Red<br>Yellow None | | | | | |
| 8 | Blue Red<br>Yellow None | | | | | |
| 9 | Blue Red<br>Yellow None | | | | | |
| 10 | Blue Red<br>Yellow None | | | | | |
| 11 | Blue Red<br>Yellow None | | | | | |
| 12 | Blue Red<br>Yellow None | | | | | |

## Table 1:Cost and Environmental Benefit Quality: Parameters

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.

### 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 Mitchell, V.G. (1998) FILTER: *A Nutrient Management Program for the Port Phillip Catchment*. Centre for Environmental Applied Hydrology, The University of Melbourne.
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### 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 | 24mm-33 mm per year |
| Wheat/Canola rotation phased with annual pasture changed to continuous Lucerne (deep rooted) | \$202-221 per ha/year | 36mm-44mm per year |
| Wheat/Canola rotation phased with annual pasture changed to continuous kikuyu pasture | \$252-271 per ha/year | 31mm-56mm per year |

Sources: Salt management options are obtained from, '*Quantitative Analysis of Benefits and Costs for Salinity Control*', by Read-Sturgess Associates, 2000, a report for the National Land and Water Resources Audit, Theme 6, Project 3.3)

**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 |

**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** | | | |
| | 82.8% | 69.4% | 86.5% | 81.6% | 4722 | 6723 |
| Ten | 85.2% | 72.6% | 90.3% | 82.1% | 3923 | 6682 |
| Individual | 84.3% | 72.4% | 88.6% | 83.1% | 4383 | 6528 |
| Sessions | 80.8% | 74.2% | 86.9% | 84.9% | 4840 | 5467 |
| in Each | 88.6% | 69.6% | 94.6% | 77.4% | 2501 | 7828 |
| Treatment | 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** | | | |
| | 89.0% | 84.6% | 94.8% | 91.3% | 59.4 | 95.6 |
| Five Individual | 89.5% | 85.4% | 94.3% | 92.7% | 68.7 | 78.2 |
| Sessions | 89.4% | 83.2% | 94.4% | 90.2% | 67.9 | 107.1 |
| in Each | 89.1% | 83.1% | 94.4% | 91.7% | 62.0 | 88.5 |
| Treatment | 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 |

**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***<br>(0.01) | 0.89***<br>(0.01) | 4785.6***<br>(407.9) |
| Dummy =1 if Uniform price treatment | -0.15***<br>(0.01) | -0.11***<br>(0.01) | 3307.1 ***<br>(386.91) |
| Dummy = 1 if site = Melbourne | 0.01<br>(0.01) | 0.02***<br>(0.01) | -645.2<br>(386.92) |
| Ln(period) | 0.01***<br>(0.002) | 0.01***<br>(0.003) | -437.0***<br>(86.95) |
| Observations | 694 | 694 | 694 |
| R-squared | 0.57 | 0.38 | 0.41 |
| **Salt Reduction Environment** | | | |
| Intercept | 0.84***<br>(0.009) | 0.90***<br>(0.006) | 101.8***<br>(6.79) |
| Dummy =1 if Uniform price treatment | -0.05***<br>(0.005) | -0.03***<br>(0.004) | 28.8***<br>(5.67) |
| Dummy = 1 if site = Melbourne | -0.01*<br>(0.005) | -0.006<br>(0.004) | 3.2<br>(5.67) |
| Ln(period) | 0.02***<br>(0.003) | 0.02***<br>(0.002) | -14.8***<br>(1.89) |
| Observations | 358 | 358 | 358 |
| R-squared | 0.26 | 0.37 | 0.28 |

Notes: Standard errors are in parentheses.
***: denotes a coefficient that is significantly different from zero at 1-percent. *: denotes a coefficient that is significantly different from zero at 10-percent.
All models are estimated with a random effects error structure, with the session as the random effect. Exception is the P-MAR model for salt reduction, for which the random effects model did not converge. We hence report OLS estimates for this model.

**Table 5: Seller Offer Function Estimates**

| **Variable** | **Discriminative Price** Treatment | | **Uniform Price Treatment** |
|---|---|---|---|
| | (1) | (2) | (3) |
| **Nitrogen Reduction Environment** | | | |
| Intercept | 1399.87***<br>(106.83) | 1626.03***<br>(182.67) | 278.25<br>(234.13) |
| Costs | 0.99***<br>(0.009) | 0.90***<br>(0.057) | 1.03***<br>(0.017) |
| Costs$^2$ | - | 0.0000070<br>(0.0000046) | - |
| Dummy = 1 if site = Melbourne | -312.49***<br>(99.69) | -312.44***<br>(99.42) | 330.33<br>(254.81) |
| Ln(period) | -142.06***<br>(22.41) | -142.09***<br>(22.41) | -157.37***<br>(41.70) |
| R-squared | 0.58 | 0.58 | 0.29 |
| Number of Observations | 8621 | 8621 | 8610 |
| **Salt Reduction Environment** | | | |
| Intercept | 11.93***<br>(1.83) | 12.26*<br>(6.51) | 16.84***<br>(3.74) |
| Costs | 1.01 ***<br>(0.006) | 1.01***<br>(0.069) | 0.99***<br>(0.009) |
| Costs$^2$ | - | 0.0000091<br>(0.00017) | - |
| Dummy = 1 if site = Melbourne | -0.98***<br>(0.02) | -0.97***<br>(0.08) | 5.59<br>(3.65) |
| Ln(period) | 0.95***<br>(0.03) | 0.95***<br>(0.03) | -6.12***<br>(0.57) |
| R-squared | 0.86 | 0.86 | 0.70 |
| Number of Observations | | | |

Notes: Standard errors are in parentheses.
***: denotes a coefficient that is significantly different from zero at 1-percent. *: denotes a coefficient that is significantly different from zero at 10-percent.
All models are estimated with a random effects error structure, with the subject as the random effect.

## Figure 1:

## All Individual Offers for Discriminative Price Treatment for the Nitrogen Reduction Environment

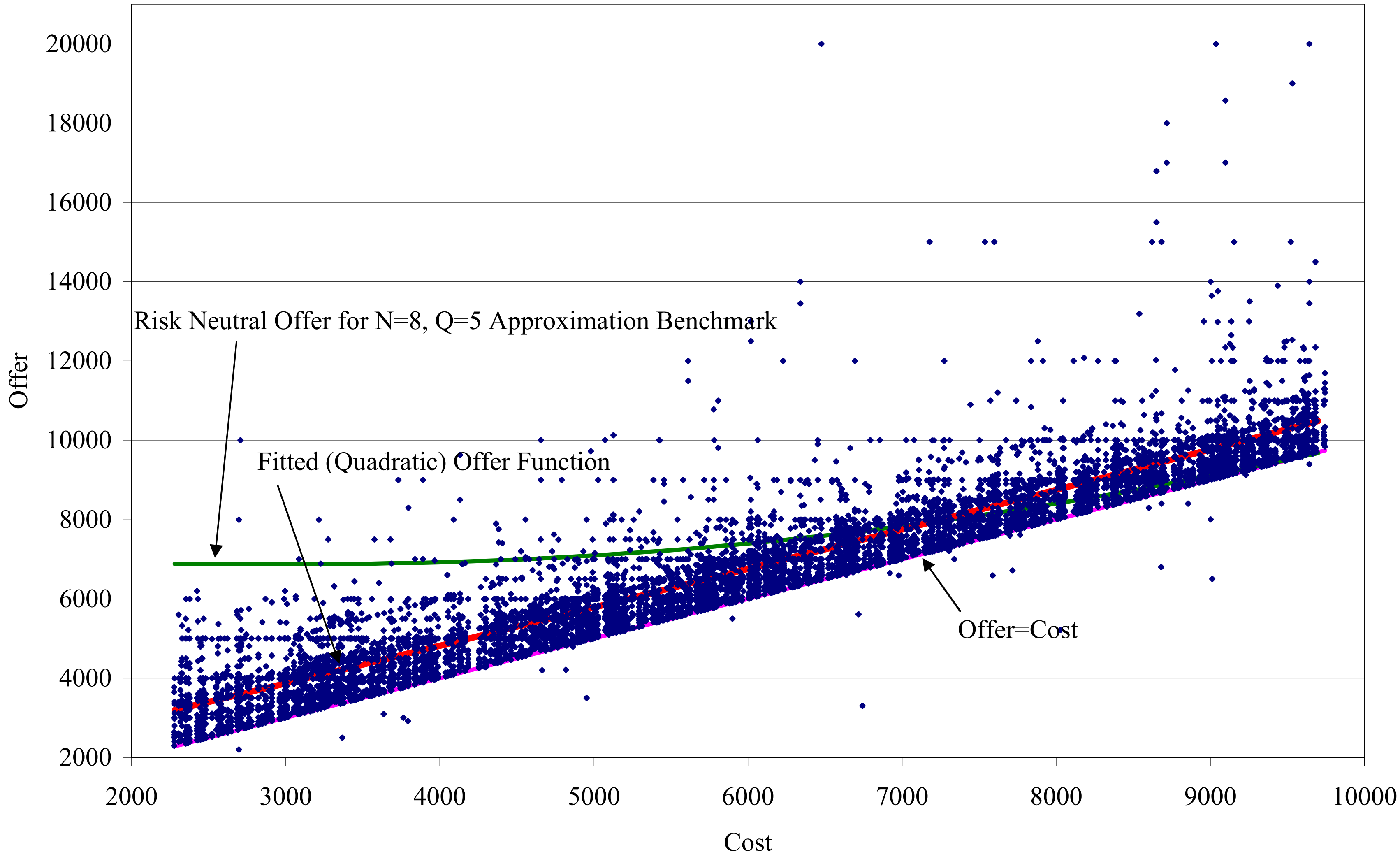


**Figure 2:**

All Individual Offers for Uniform Price Treatment in Nitrogen Reduction Environment

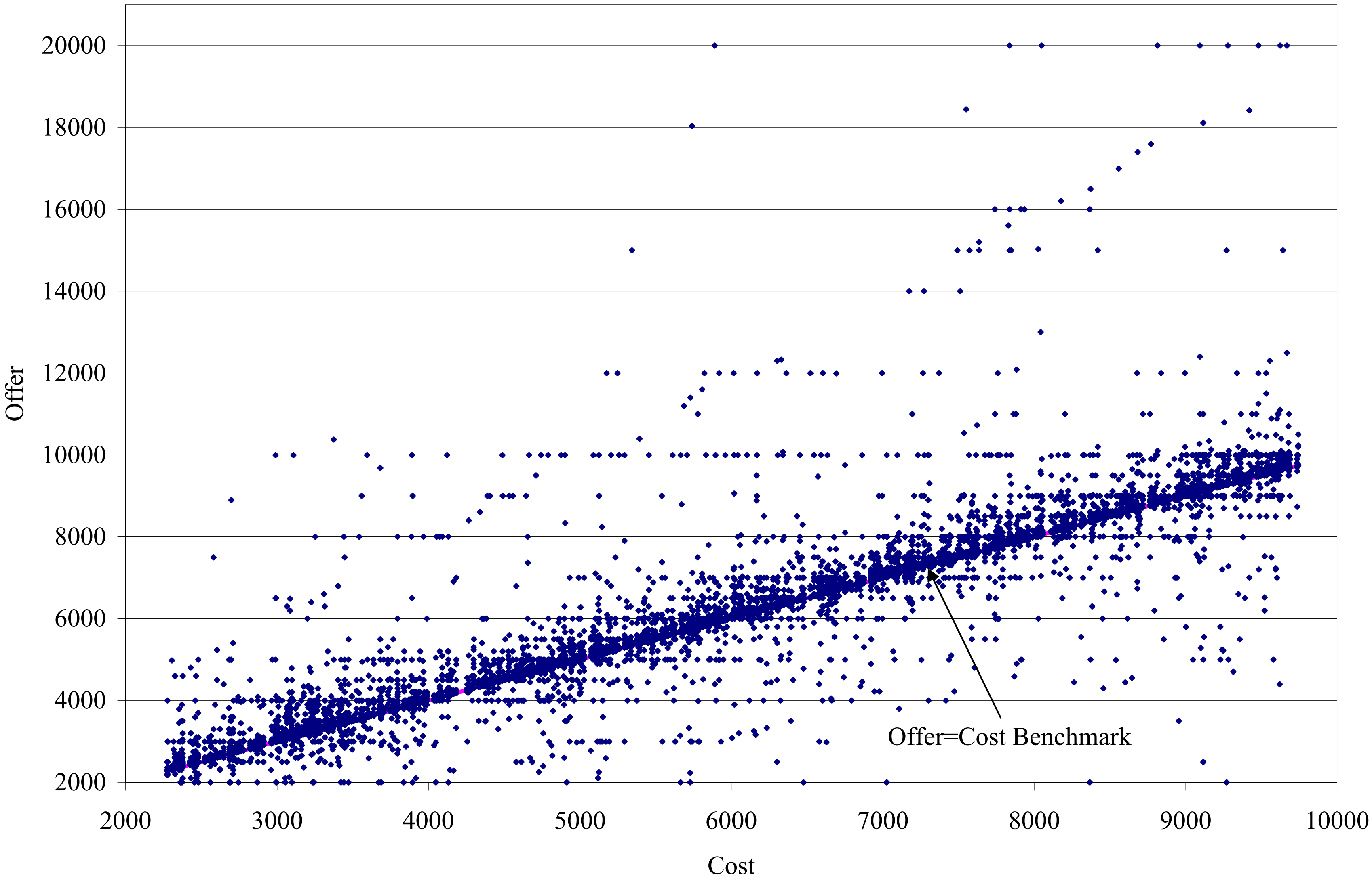


**Figure 3A: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Nitrogen Environment)**

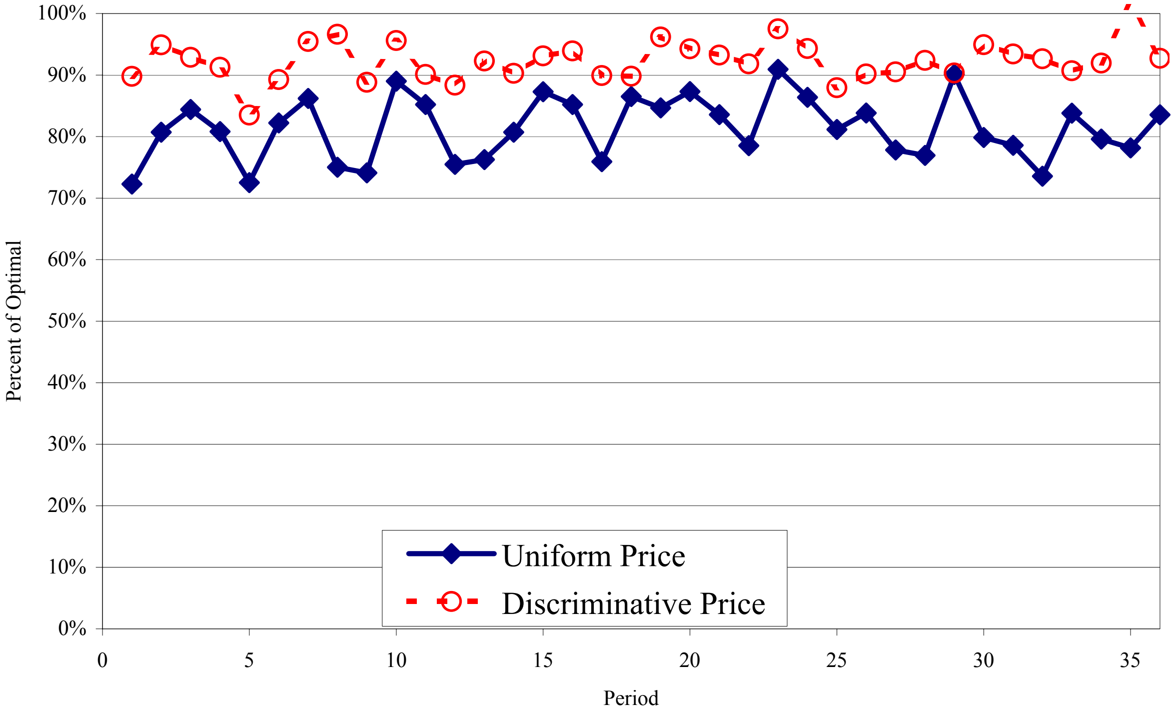


**Figure 3B: Percentage of Maximum Abatement Realized, by Treatment for Each Period (Salinity Environment)**

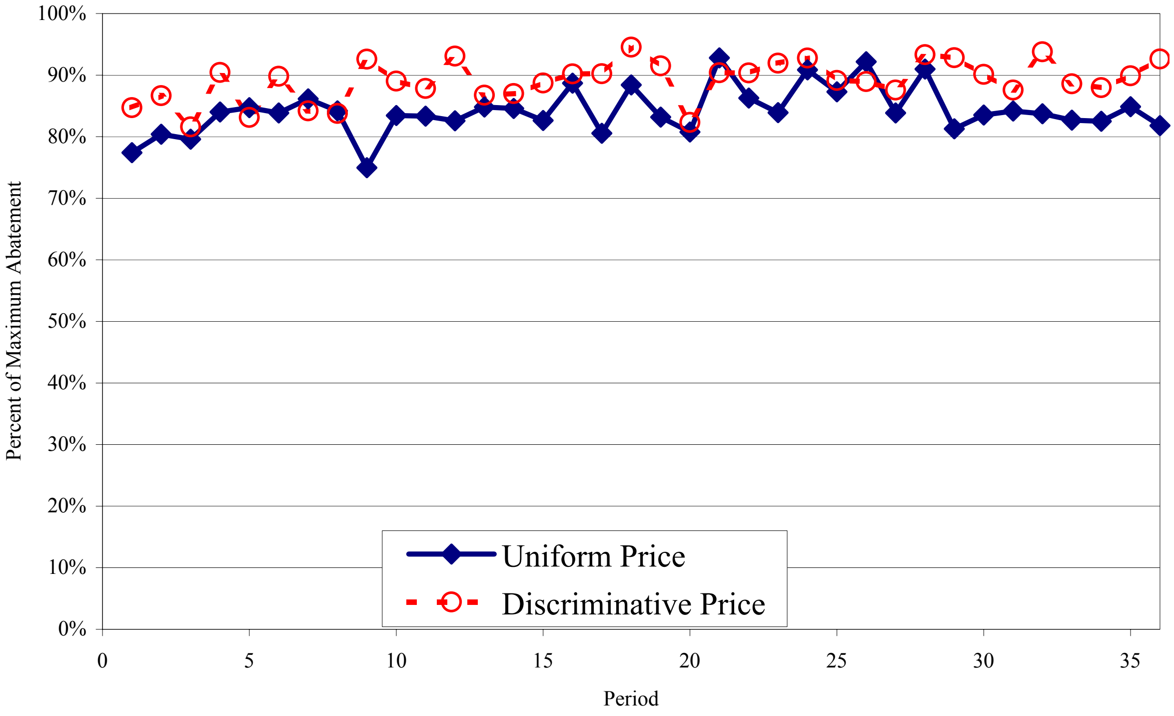


**Figure 4A: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Nitrogen Environment)**

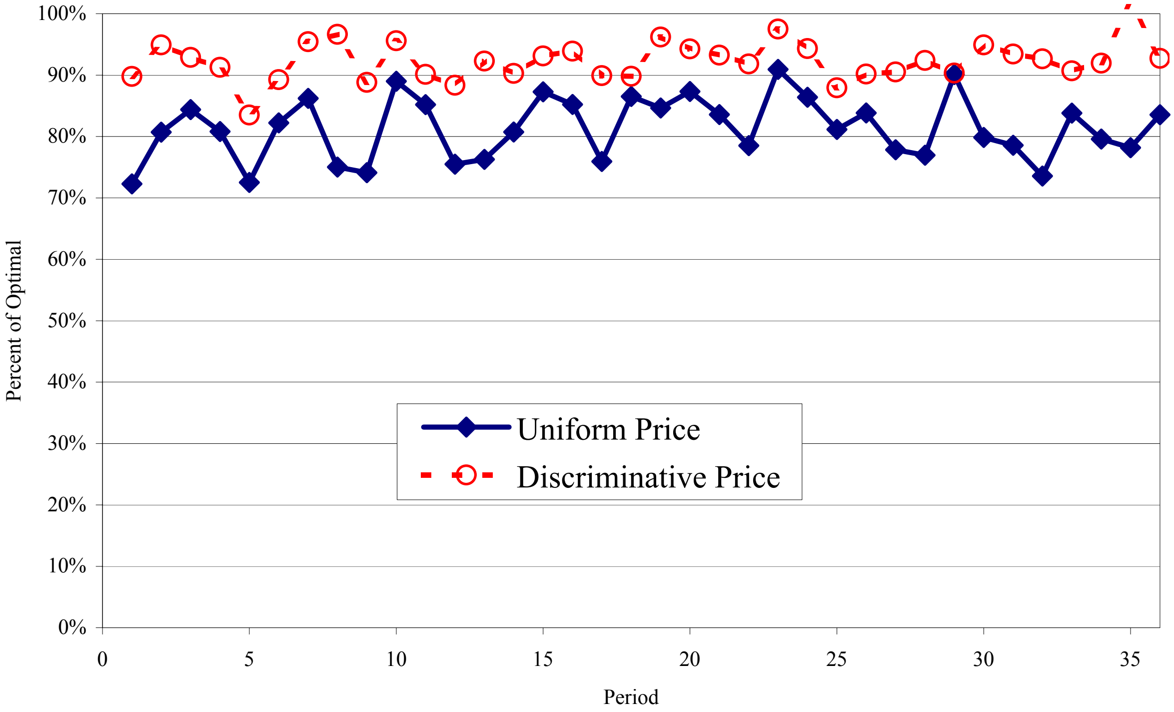


**Figure 4B: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Salinity Environment)**

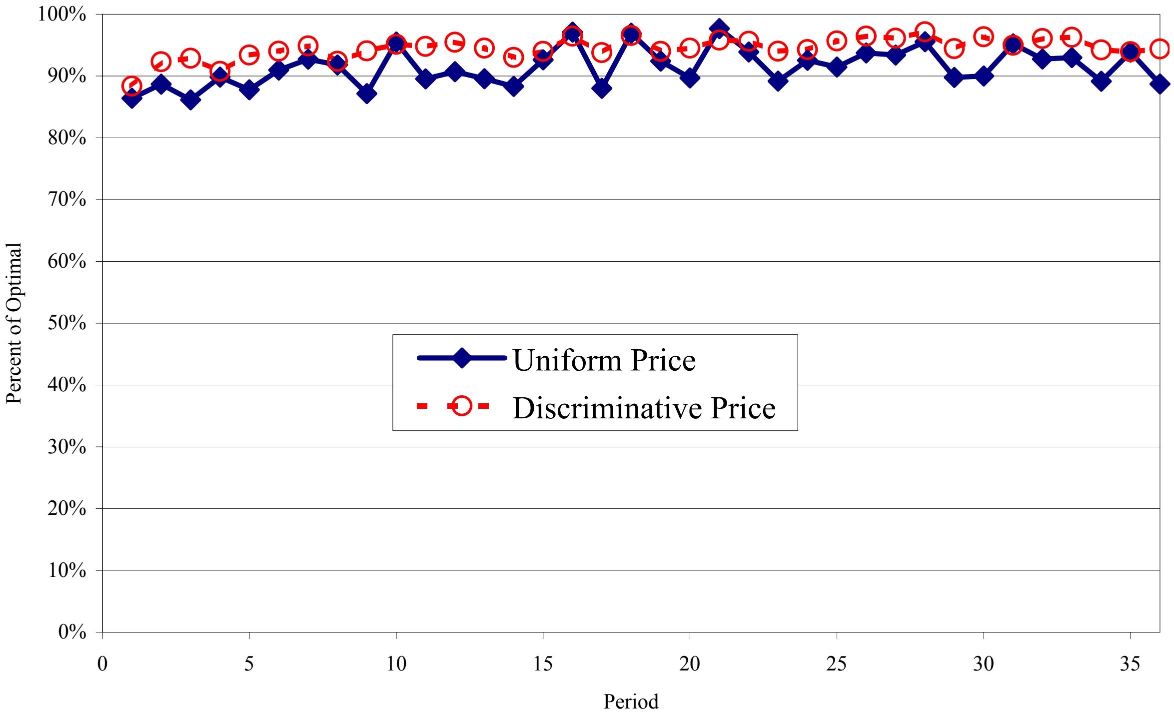


**Figure 5A: Average Seller Profits, by Treatment for Each Period (Nitrogen Environment)**

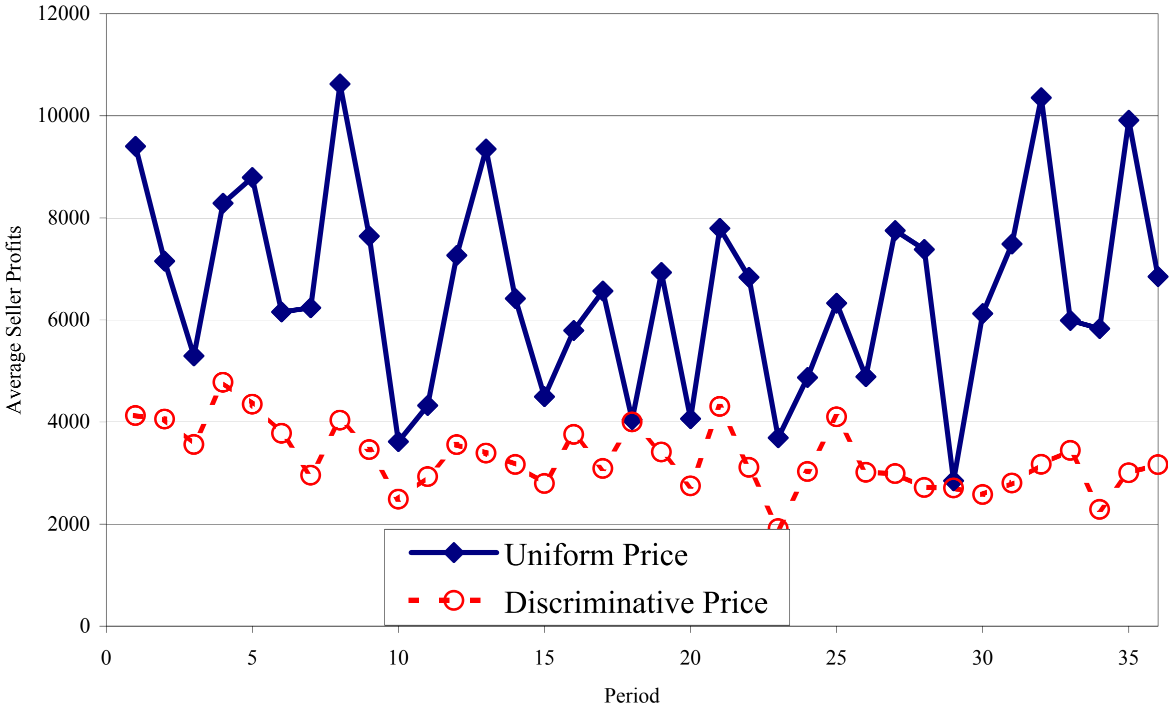


**Figure 5B: Average Seller Profits, by Treatment for Each Period (Salinity Environment)**

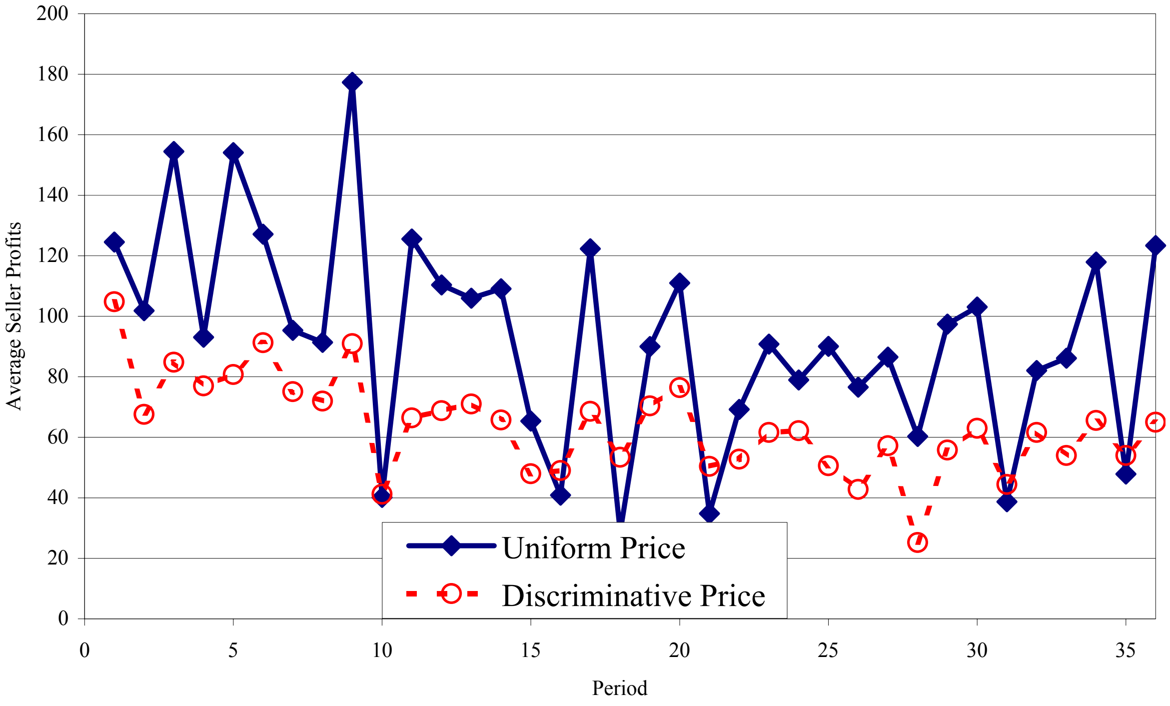
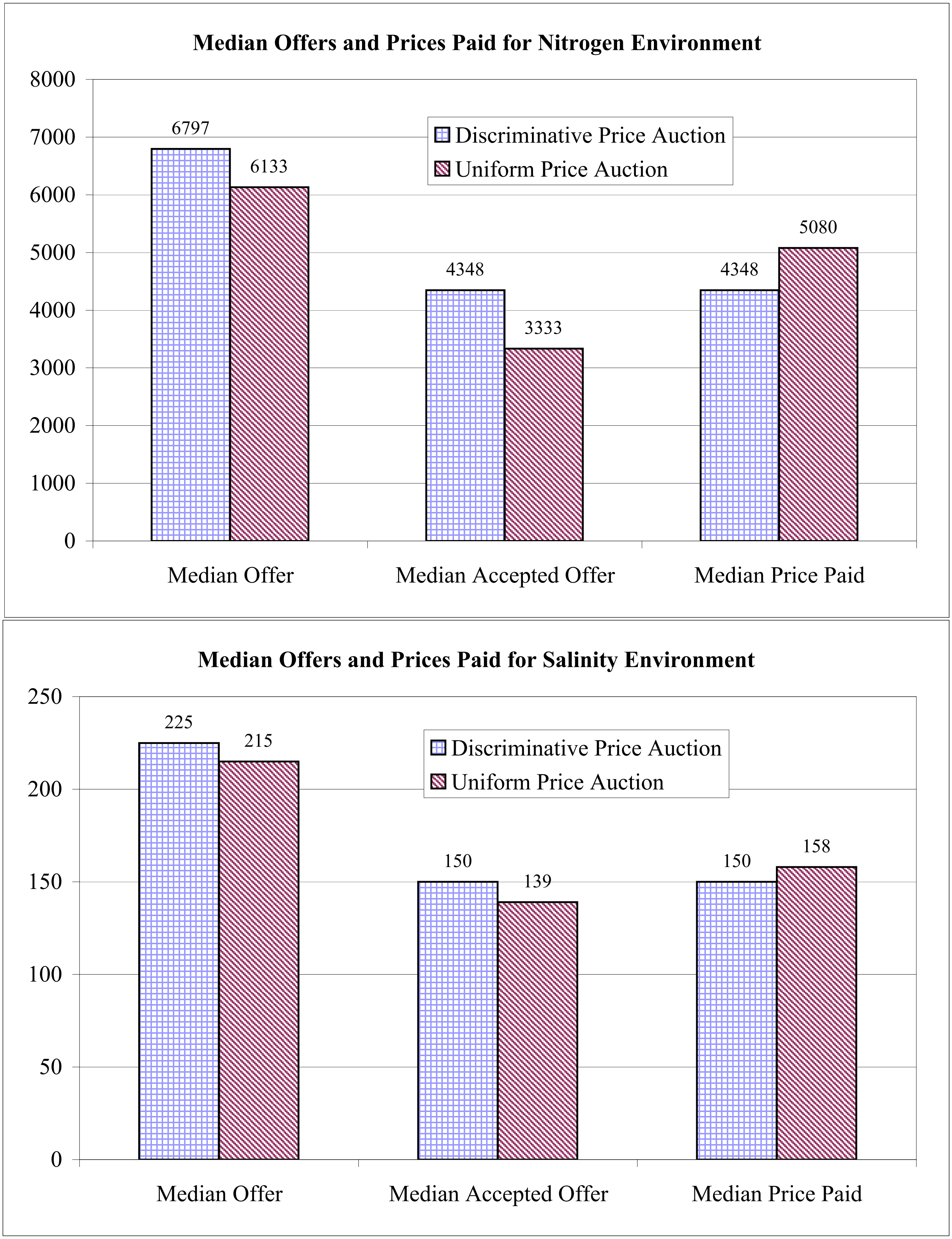


**Figure 6: Median Offers and Prices Paid**



## 1. 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 like 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 mitigate 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 "environmental procurement:" uniform price auctions and discriminative price auctions. Landowners offer projects that generate environmental improvement in these auctions. More specifically, sellers offer projects with different costs and different levels of environmental benefits to the regulator, who is the buyer and ranks the offers on the basis of their offer price and the potential 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. All participants submit sealed offers, and in the uniform price auction the successful sellers receive a uniform price (per unit of environmental benefit) equal to the lowest rejected offer. In the discriminative price auction, each successful seller receives 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 equals 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 receive a market-clearing price that exceeds their offer and 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 these types 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, 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 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 et al. (1985) find that subjects failed to follow their dominant strategy of bidding equal to values in multiple unit, uniform price, sealed bid auctions. Cox et al. (1982) and Kagel et al. (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

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[1] For example, Holt (1980) shows that for risk averse buyers, the discriminative auction results in higher expected revenue, and Maskin and Riley (2000) relax the assumption of symmetry and assume that the buyers' reservation values are not identically distributed. In this case the revenue equivalence theorem does not hold and the ranking of different auctions would depend on how the distributions vary across buyers. Some researchers have argued that the uniform price auction has a lower winner's curse in common value environments and results in greater revenue to the seller than would a discriminative auction (see Milgrom, 1989; Bikhchandani and Huang, 1993). However this work was based on a single-unit auction theory and Back and Zender (1993) show that this result is critically dependent on the assumption that the good was indivisible.

the assumptions for the revenue equivalence theorem. For example, the auctions studied here assume that sellers offer multiple projects for sale, but because of the interaction of the environmental benefits across projects the regulator would choose at most one project from each seller.[2] In this setting, sellers may not make optimal offers independently on 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 regulator 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. Moreover, the fixed budget constraint for the regulator 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

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[2] For example, the installation of grassed swale drains with sediment traps to reduce nutrient loads would reduce the environmental benefit of decreased fertilizer applications. The benefits of these two alternative mitigation strategies are therefore interrelated, but the benefits would be evaluated separately in the auction for simplicity. To avoid the complication of project interactions we limit each seller to supply at most one project.

performance, even though the discriminative auction rules lead to higher offer prices. The empirical research issues examined in this paper are crucial to understand better 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 like 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.

## 2. Experimental Design

### 2.1 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 percent of the land) and contributes to 53 percent 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 quality 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 the costs of their land use change projects, but they do not know the associated quality (environmental benefit). We do not reveal the environmental benefits to sellers 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. In order to enhance the external validity of the experiment, we also do not provide sellers with any information about other sellers' costs and quality or the distributions that are used to generate the costs and qualities. They are told simply that the costs and quality levels would be different across sellers and could change from period to period. They also do not know the regulator's budget, which is fixed at $25,000 experimental dollars per period in the nitrogen reduction environment and $1000 experimental dollars per period in the salt reduction environment.

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[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).

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.

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 format and 7 in the discriminative price format) and 15 conducted at Purdue (7 in the uniform price format and 8 in the discriminative price format). All sessions have 36 trading periods. In each session eight seller subjects offer items in a computerized sealed offer auction, so across all 30 sessions a total of 240 different subjects participated. 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 below for a specific example. Once the allocation is made the results are reported to the subjects electronically on their web browser.

As is usual in experimental economics, we use neutral terminology in the instructions to refer to the different items that sellers could offer. The appendix contains the experiment instructions. 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 1000 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.

### 2.2 Treatments and Predictions

Our goal in this experiment is to compare the performance characteristics of uniform price 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 that (2) total expenditures do not exceed the overall auction budget.[4]

Table 2 presents an example from period 31 in two sessions to illustrate the rules. In both auction formats the algorithm first calculates ratio of the offer price to the environmental 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

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[4] 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.

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 2999, 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 environmental 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.[5] For the auction budgets and the

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[5] 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

actual realized costs and environmental benefits draws employed in the experiment, under full cost revelation these uniform price auction rules extract 72.4 percent of the maximum possible abatement in the nitrogen reduction environment and 86.6 percent 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.[6] 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 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 below 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 environmental benefits draws employed in the experiment, in the nitrogen reduction environment these discriminative price auction rules extract only 54.8 percent

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incomplete information in any field implementation—makes the identification of this misrepresentation incentive rather implausible.

[6] In the nitrogen reduction environment, exactly $Q$=5 units were sold in 64 percent of the periods, and the $Q$ sold was 4, 5 or 6 in 99 percent 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.

of the maximum possible abatement if this offer function approximation is accurate. The corresponding benchmark for the salinity reduction environment is 63 percent 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 percent and 86.6 percent 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.

## 3. Results

Figures 1 and 2 present an overview of the offer data for the nitrogen reduction environment.[7] 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+$1000, 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. Figure 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, nearly two thirds (67%) of the offers are above cost and 85% of the offers are within $14 of cost. In the first subsection we

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[7] 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.

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 Subsection 3.2.

### 3.1 Overall Market Performance

Following Cason et al. (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.[8]

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

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[8] 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, 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 percent of the maximum possible abatement.

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). Similarly for the salinity reduction environment, the lowest efficiency across the 5 discriminative price sessions (88.3%) is greater than the highest efficiency in the uniform price treatment (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 that controls 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. We also include ln(period) to allow the model to capture differences in performance across periods. The negative and highly significant estimate on the uniform price treatment dummy variable indicates that P-MAR efficiency is about 15 percentage points 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.

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 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 percentage points higher in the discriminative price auction in the nitrogen reduction environment and 3 percentage points higher in the salinity reduction environment. The positive and significant ln(period) term indicates that like P-MAR, P-OCER increases across time.

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 (4840) is less than the lowest seller profits in the uniform price auction (5467), 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) is less 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 nitrogen reduction environment and by nearly 29 experimental dollars in the salinity reduction environment. These average differences in profits across auction institutions represent approximately 80 percent and 20 percent 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.

### 3.2 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 i.e., 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 environment. 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 treatment, since the theoretical approximation in Figure 1 suggests a nonlinear specification for this institution.[9] Note, however, that the nonlinear term ($\text{costs}^2$) 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 and discriminative price treatments. In fact, the coefficient on the cost variable is not significantly different from one for either auction format in either environment, 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

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[9] In particular, the theoretical approximation shown in Figure 1 for the nitrogen reduction environment is fit very accurately with the quadratic specification $\text{Offer} = 7573 - 0.429\text{Cost} + 0.000067\text{Cost}^2$.

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. For the salinity reduction environment, the offer function intercept is significantly positive for both uniform and discriminatory price sessions; however, offers increase over time in the discriminatory price 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 importantly, 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 price auction performed better than the uniform price auction.

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.

## 4. Discussion

Auctions allow an environmental regulator and landholders to use information about environmental benefits and land use management costs to help protect the environment. In the auctions testbedded here the agency uses 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 sellers 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 is 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 environmental regulator can buy 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. 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 landholders, using the environmental terminology—and the relevant value judgments that environmental protection and property rights evoke in this 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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## Appendix: Instructions for Uniform Price Auction Treatment (Discriminative Price Auction instructions are similar)

### General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of ______ Experimental Dollars = 1 real Dollar. The important thing to remember is that the more experimental dollars you earn, the more real dollars that you take home at the end of the experiment.

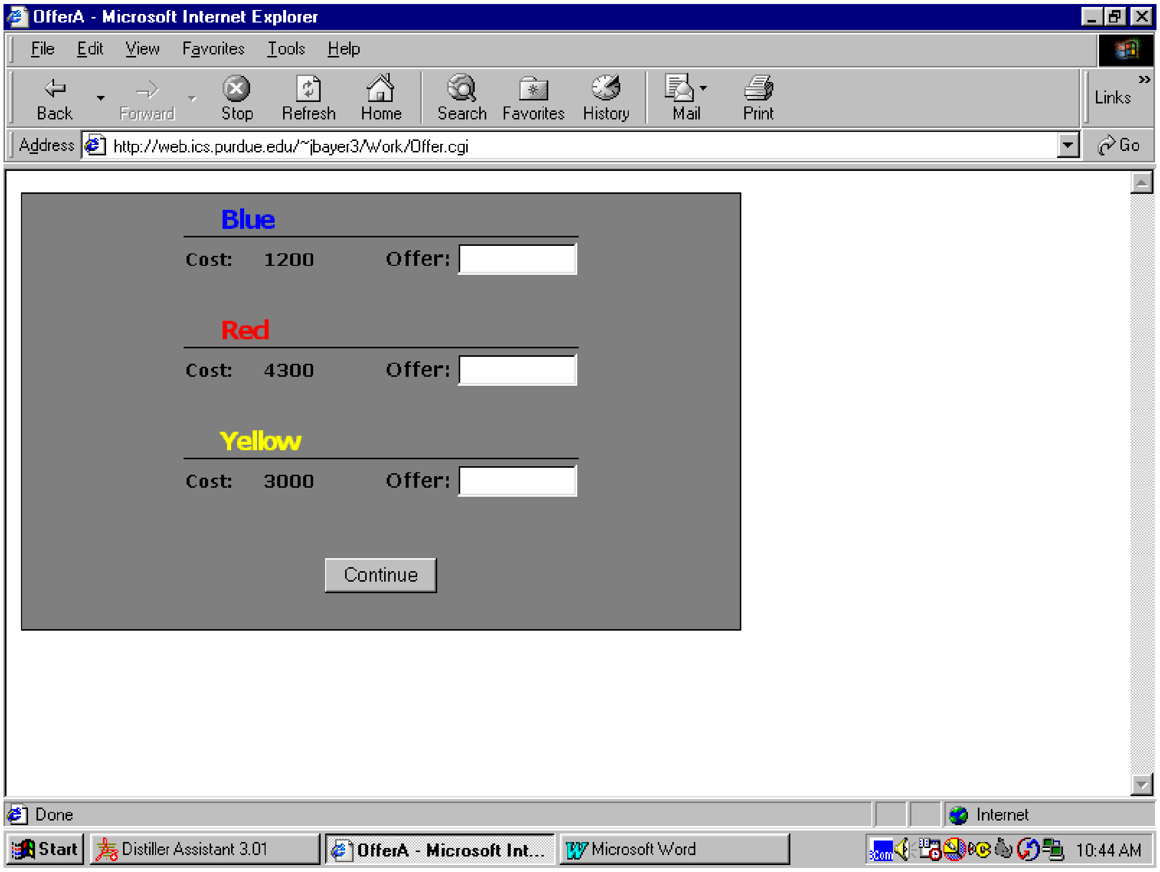
We are going to conduct a set of auctions in which you will be a seller in a sequence of periods. During each auction period you will sell up to one item. You have up to three types of items to sell, called Blue, Red and Yellow items. These items have different levels of "quality" that are valued differently by the experimenter, who is the buyer. Your quality levels may change from period to period, and they may be different from the quality levels of other participants. You can sell only one item per period, and if you sell that item then you must pay that item's cost. If you do not sell any item in a period then your earnings are zero for that period. Notice that you do not pay an item's cost unless you sell that item. Your costs may also change from period to period, and they may be different from the costs of other participants.

Your costs for each of the three types of items are displayed on your computer screen each period, as shown in the example figure on the next page. The profits from sales (which are yours to keep) are computed by taking the difference between the sale price of an item and the cost of that item. (How price is determined will be explained shortly.) That is, [your earnings = (sale price of item) – (cost of item)].

Suppose, for example, that the cost for your Blue item is 110. If you sell your Blue item at a price of 160, your earnings are:

Earnings = 160 – 110 = 50

Notice that if you sell an item for a price that is less than its cost, then you lose money on that sale.



Blue
Cost: 1200 Offer:

Red
Cost: 4300 Offer:

Yellow
Cost: 3000 Offer:

Continue

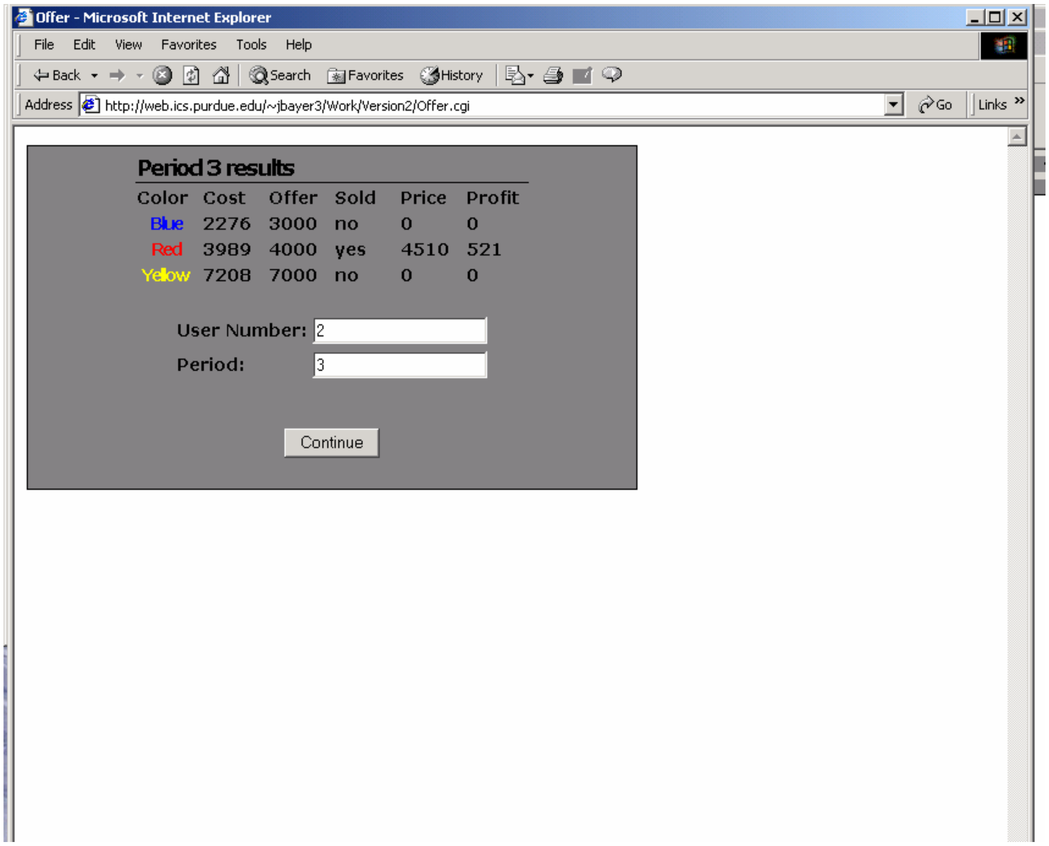
## How Your Price is Determined

The price you receive if you sell an item and which (if any) item you sell is determined using a "sealed offer" auction. In each period you submit an "offer sheet" through your web browser, which lists the minimum amount that you wish to receive for each item. [Do not use a dollar sign when entering your offers on your web browser.] If you sell an item, you will receive a price that is greater than or equal to the price you indicated on your offer sheet for that item.

After everyone submits their offer sheets, the experimenter's computer then ranks the offers on the basis of the offer price and the quality of the items. The experimenter purchases the lowest priced items per unit of quality, spending all of the fixed and constant (and unknown to you) "budget" that is available in the auction. (In the case of a "tie," where two or more items are offered at the same per-quality-unit price but the experimenter cannot purchase them all, the computer randomly determines which item or items are purchased.) Sometimes you may sell an item that you offer at a higher price than some other item when that item has a higher quality. Sometimes you may not sell any item. Remember, the experimenter will buy no more than one item from each seller.

The price you receive if you sell an item is NOT determined by any of the offers you submit. Instead, everyone who sells an item in a period receives the same price per unit of quality, and this price is set by the lowest price per unit of quality submitted by a seller who had all of his or her offers REJECTED. Thus, your profit is not decreased by submitting offers lower than the lowest rejected offer that determines the price. The lower your offers the more likely you will have an offer below the lowest rejected offer and therefore make a successful sale.

In other words, by submitting lower offers you increase the likelihood that you make a sale, but lower offers do not directly reduce the price you receive since the price you receive is determined by a different (rejected) seller's offer. As long as you make offers that are no lower than your items' costs, you have no chance of losing money because if you sell an item you receive a price that is at least as high as your offer price. But if you make offers that are lower than your costs you run the risk of selling at a price less than your cost. This is because the lowest rejected offer could then also be less than your cost and result in a price for you that is less than your cost.



**Period 3 results**

| Color | Cost | Offer | Sold | Price | Profit |
|---|---|---|---|---|---|
| Blue | 2276 | 3000 | no | 0 | 0 |
| Red | 3989 | 4000 | yes | 4510 | 521 |
| Yellow | 7208 | 7000 | no | 0 | 0 |

User Number: 2

Period: 3

After each auction period, the experimenter will tell you when to click the "Continue" button to display the auction results. An example results screen is shown above. It indicates which (if any) item you sell by a "yes" in the Sold column. The results screen also displays the price you receive and the profit on the sale. Circle the color of the one item (if any) that is accepted in the column (1) of your Personal Record Sheet. Then enter the cost of this item, your offer price, the price you receive for the item, and your profit in the other columns of the record sheet. Use a calculator to keep track of your total (cumulative) Experimental Dollar earnings in the rightmost column (6) of your Record Sheet. The results page will automatically increment the period number by 1 for the next period, so after you write down your results on your Record Sheet you should simply press Continue to move to the next period.

**Summary**

- Seller earnings on a sold item = sale price of item – cost of item
- Sellers have three types of items, which can have different costs and quality levels valued differently by the experimenter (who is the buyer). Your costs are shown on your computer screen each period.
- Costs and quality levels may change from period to period and vary across sellers.
- Sellers submit offer prices for three types of items, but the experimenter will buy no more than one item from each seller.
- The experimenter purchases the lowest price items per unit of quality, and spends a constant budget in every auction.
- If you sell an item the price you receive is determined by the lowest price per unit of quality offered by a seller who has all of his or her offers rejected in the auction.

Are there any questions now before we begin the experiment?

**Personal Record Sheet for User Number ____________**

| Period Number | Circle Color Sold (if any) (column 1) | Cost of Sold Item (column 2) | Offer Price for Sold Item (column 3) | Price Received for Sold Item (column 4) | Profit this Period (col. 4 – col. 2) (column 5) | Cumulative Profit (all Periods) (column 6) |
|---|---|---|---|---|---|---|
| 1 | Blue Red<br>Yellow None | | | | | |
| 2 | Blue Red<br>Yellow None | | | | | |
| 3 | Blue Red<br>Yellow None | | | | | |
| 4 | Blue Red<br>Yellow None | | | | | |
| 5 | Blue Red<br>Yellow None | | | | | |
| 6 | Blue Red<br>Yellow None | | | | | |
| 7 | Blue Red<br>Yellow None | | | | | |
| 8 | Blue Red<br>Yellow None | | | | | |
| 9 | Blue Red<br>Yellow None | | | | | |
| 10 | Blue Red<br>Yellow None | | | | | |
| 11 | Blue Red<br>Yellow None | | | | | |
| 12 | Blue Red<br>Yellow None | | | | | |

## Table 1:Cost and Environmental Benefit Quality: Parameters

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.

### 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 Mitchell, V.G. (1998) FILTER: *A Nutrient Management Program for the Port Phillip Catchment*. Centre for Environmental Applied Hydrology, The University of Melbourne.
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### 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 | 24mm-33 mm per year |
| Wheat/Canola rotation phased with annual pasture changed to continuous Lucerne (deep rooted) | \$202-221 per ha/year | 36mm-44mm per year |
| Wheat/Canola rotation phased with annual pasture changed to continuous kikuyu pasture | \$252-271 per ha/year | 31mm-56mm per year |

Sources: Salt management options are obtained from, '*Quantitative Analysis of Benefits and Costs for Salinity Control*', by Read-Sturgess Associates, 2000, a report for the National Land and Water Resources Audit, Theme 6, Project 3.3)

## 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 |

**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 Individual Sessions 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 |

**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***<br>(0.01) | 0.89***<br>(0.01) | 4785.6***<br>(407.9) |
| Dummy =1 if Uniform price treatment | -0.15***<br>(0.01) | -0.11***<br>(0.01) | 3307.1 ***<br>(386.91) |
| Dummy = 1 if site = Melbourne | 0.01<br>(0.01) | 0.02***<br>(0.01) | -645.2<br>(386.92) |
| Ln(period) | 0.01***<br>(0.002) | 0.01***<br>(0.003) | -437.0***<br>(86.95) |
| Observations | 694 | 694 | 694 |
| R-squared | 0.57 | 0.38 | 0.41 |
| **Salt Reduction Environment** | | | |
| Intercept | 0.84***<br>(0.009) | 0.90***<br>(0.006) | 101.8***<br>(6.79) |
| Dummy =1 if Uniform price treatment | -0.05***<br>(0.005) | -0.03***<br>(0.004) | 28.8***<br>(5.67) |
| Dummy = 1 if site = Melbourne | -0.01*<br>(0.005) | -0.006<br>(0.004) | 3.2<br>(5.67) |
| Ln(period) | 0.02***<br>(0.003) | 0.02***<br>(0.002) | -14.8***<br>(1.89) |
| Observations | 358 | 358 | 358 |
| R-squared | 0.26 | 0.37 | 0.28 |

Notes: Standard errors are in parentheses.

***: denotes a coefficient that is significantly different from zero at 1-percent. *: denotes a coefficient that is significantly different from zero at 10-percent.

All models are estimated with a random effects error structure, with the session as the random effect. Exception is the P-MAR model for salt reduction, for which the random effects model did not converge. We hence report OLS estimates for this model.

**Table 5: Seller Offer Function Estimates**

| **Variable** | **Discriminative Price** Treatment | | **Uniform Price Treatment** |
|---|---|---|---|
| | (1) | (2) | (3) |
| **Nitrogen Reduction Environment** | | | |
| Intercept | 1399.87***<br>(106.83) | 1626.03***<br>(182.67) | 278.25<br>(234.13) |
| Costs | 0.99***<br>(0.009) | 0.90***<br>(0.057) | 1.03***<br>(0.017) |
| $\text{Costs}^2$ | - | 0.0000070<br>(0.0000046) | - |
| Dummy = 1 if site = Melbourne | -312.49***<br>(99.69) | -312.44***<br>(99.42) | 330.33<br>(254.81) |
| Ln(period) | -142.06***<br>(22.41) | -142.09***<br>(22.41) | -157.37***<br>(41.70) |
| R-squared | 0.58 | 0.58 | 0.29 |
| Number of Observations | 8621 | 8621 | 8610 |
| **Salt Reduction Environment** | | | |
| Intercept | 11.93***<br>(1.83) | 12.26*<br>(6.51) | 16.84***<br>(3.74) |
| Costs | 1.01 ***<br>(0.006) | 1.01***<br>(0.069) | 0.99***<br>(0.009) |
| $\text{Costs}^2$ | - | 0.0000091<br>(0.00017) | - |
| Dummy = 1 if site = Melbourne | -0.98***<br>(0.02) | -0.97***<br>(0.08) | 5.59<br>(3.65) |
| Ln(period) | 0.95***<br>(0.03) | 0.95***<br>(0.03) | -6.12***<br>(0.57) |
| R-squared | 0.86 | 0.86 | 0.70 |
| Number of Observations | | | |

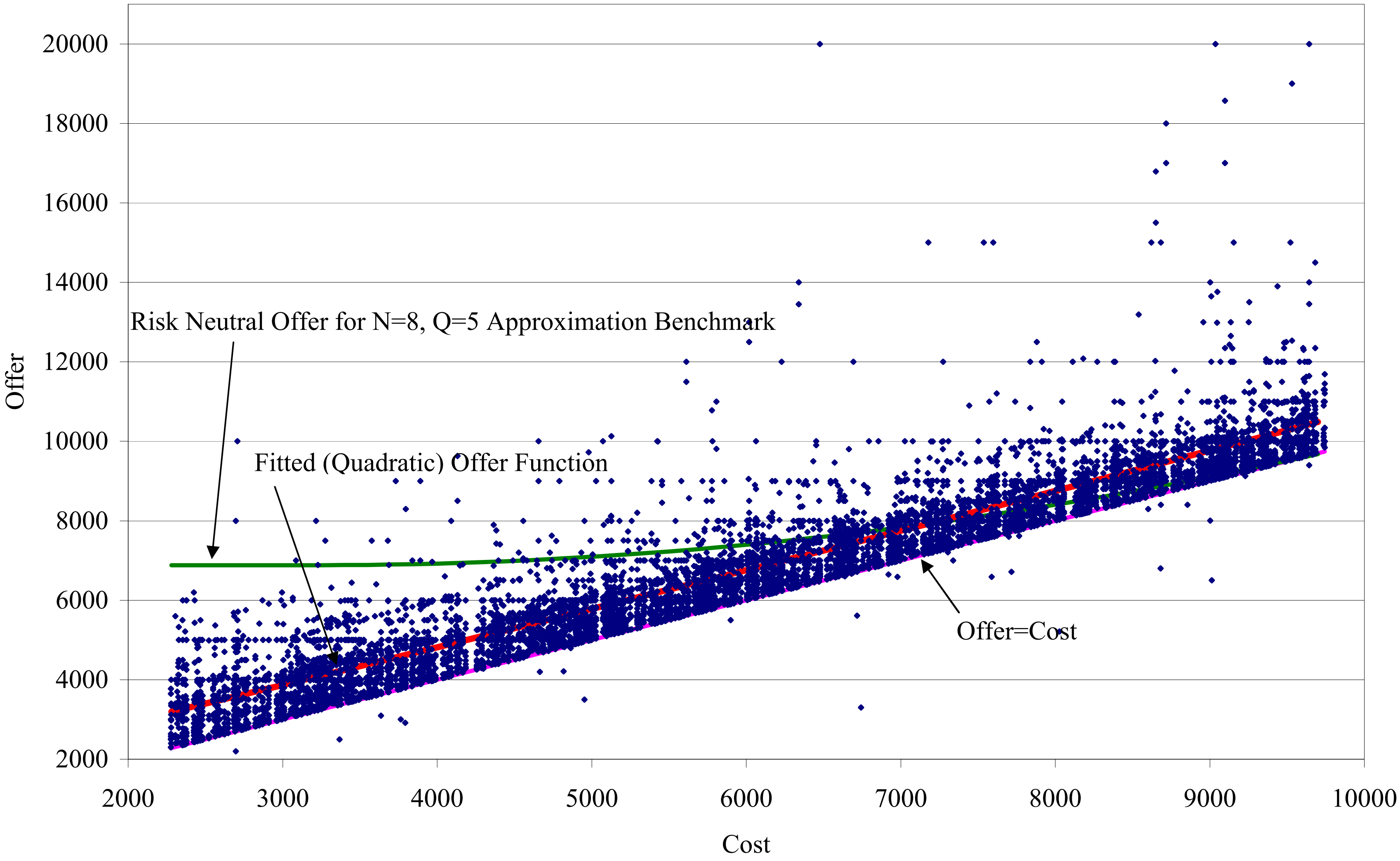
Notes: Standard errors are in parentheses.

***: denotes a coefficient that is significantly different from zero at 1-percent. *: denotes a coefficient that is significantly different from zero at 10-percent.

All models are estimated with a random effects error structure, with the subject as the random effect.

**Figure 1:**

**All Individual Offers for Discriminative Price Treatment for the Nitrogen Reduction Environment**



## Figure 2:

All Individual Offers for Uniform Price Treatment in Nitrogen Reduction Environment

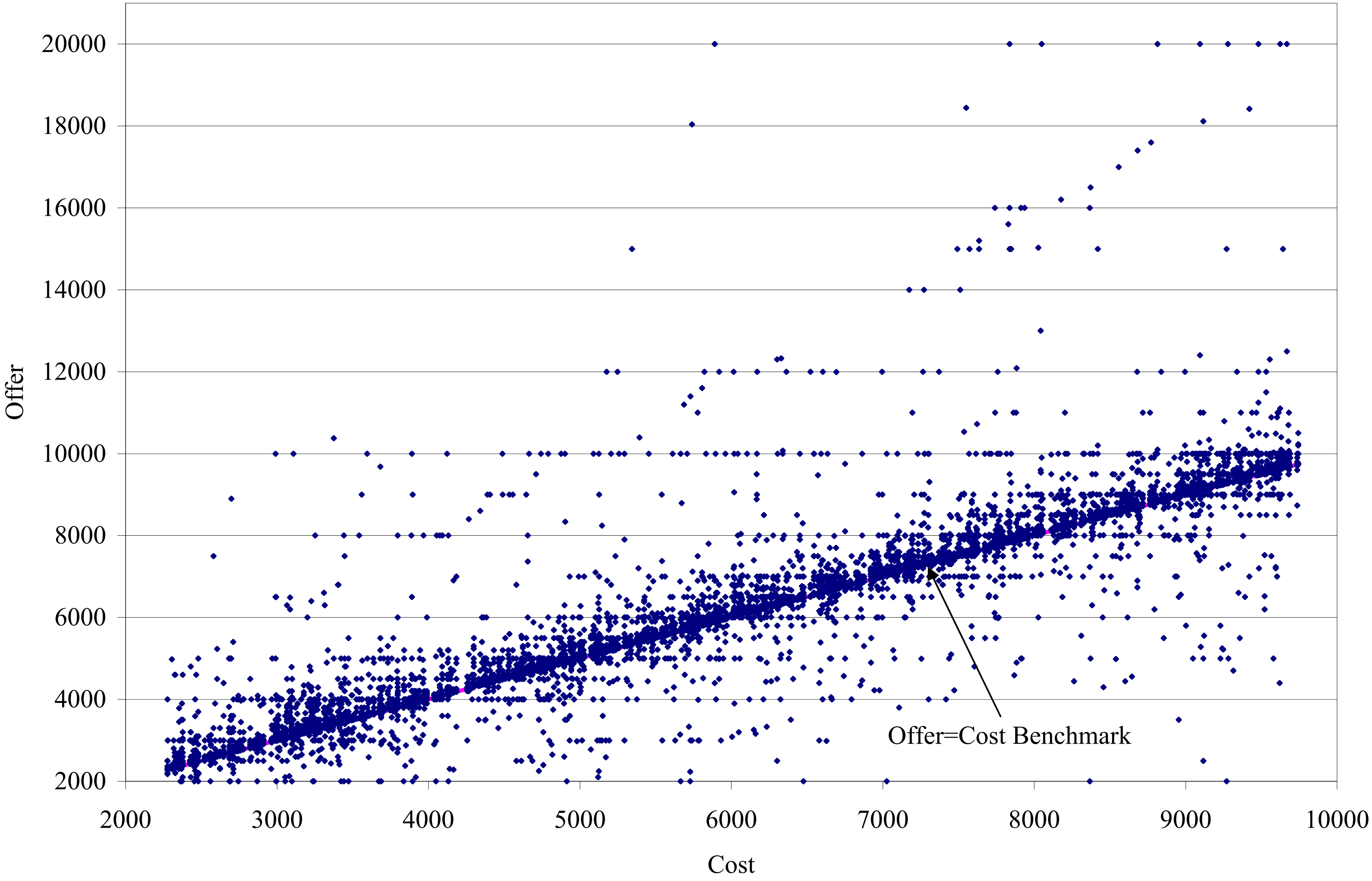


**Figure 3A: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Nitrogen Environment)**

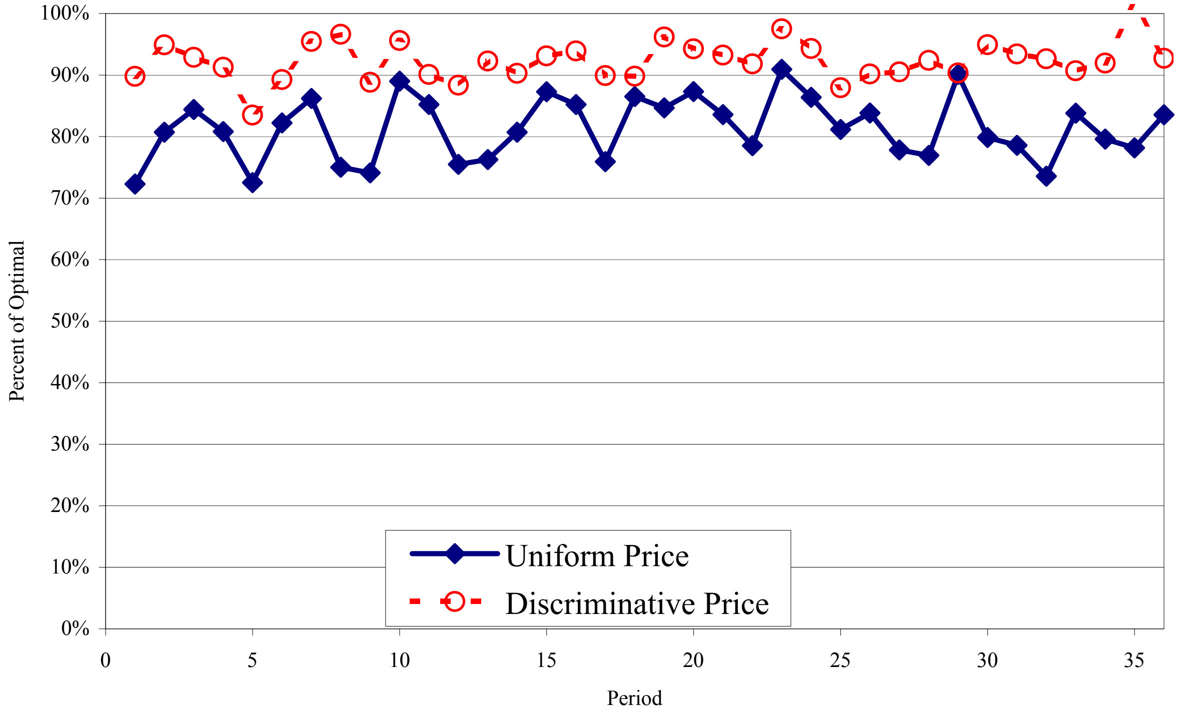


**Figure 3B: Percentage of Maximum Abatement Realized, by Treatment for Each Period (Salinity Environment)**

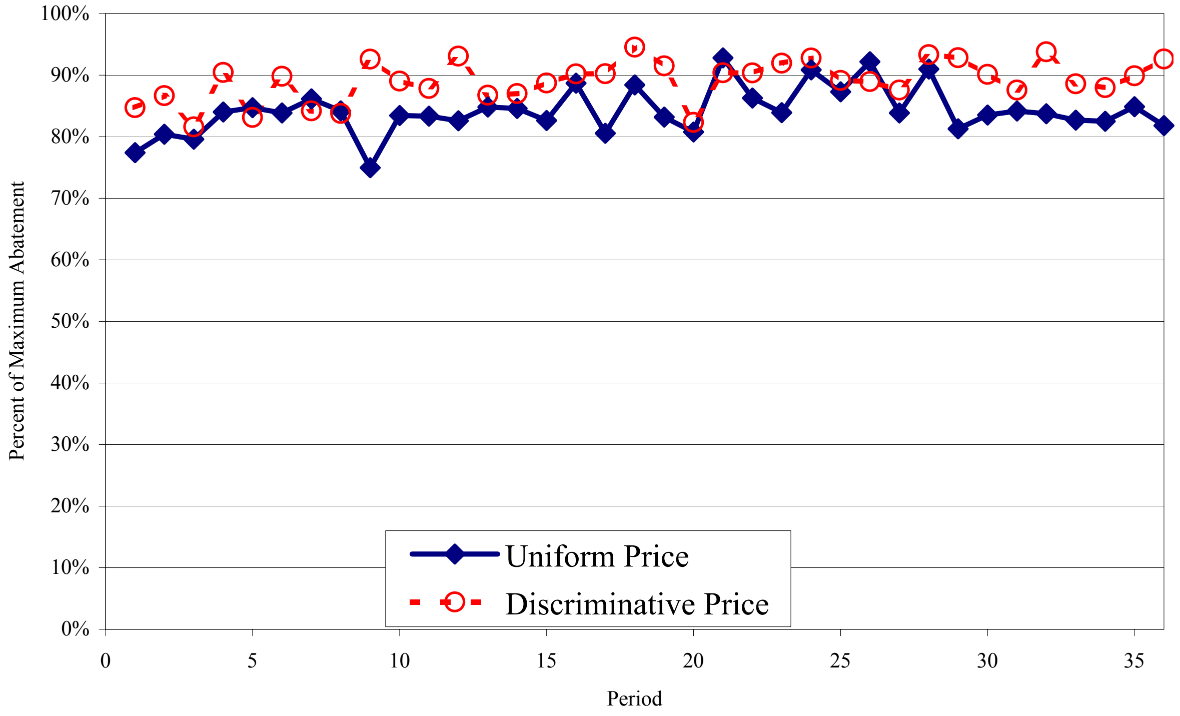


Figure 4A: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Nitrogen Environment)

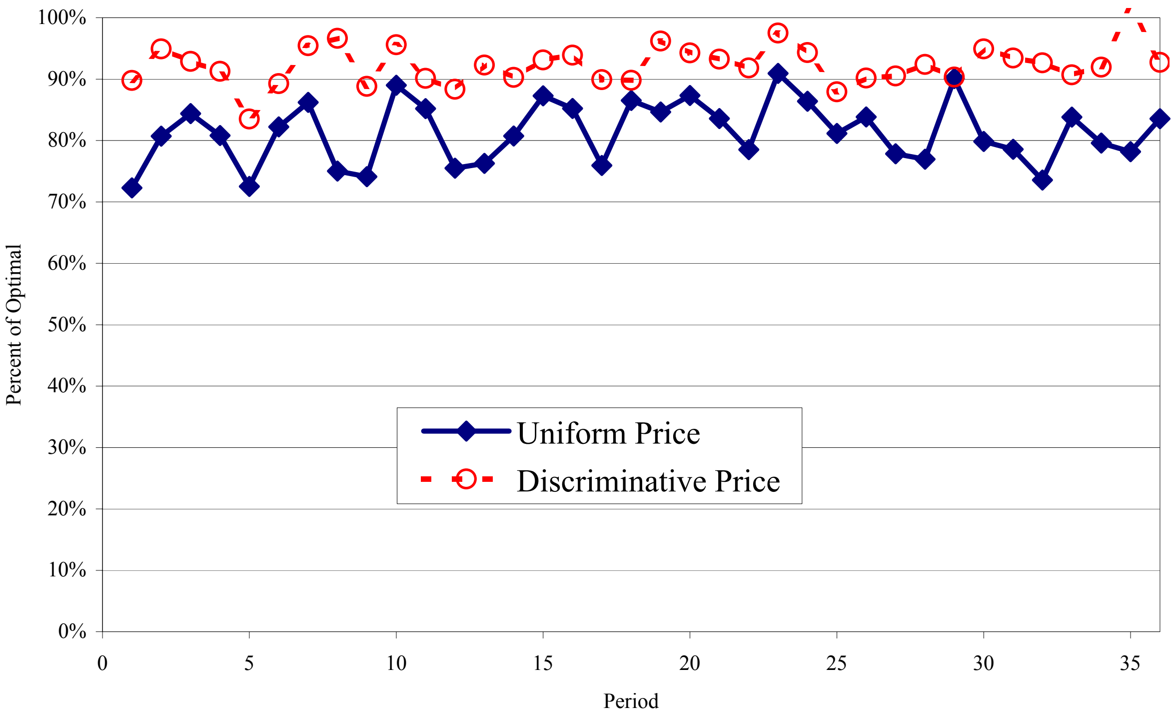


Figure 4B: Percentage of Optimal Cost-Effectiveness Realized, by Treatment for Each Period (Salinity Environment)

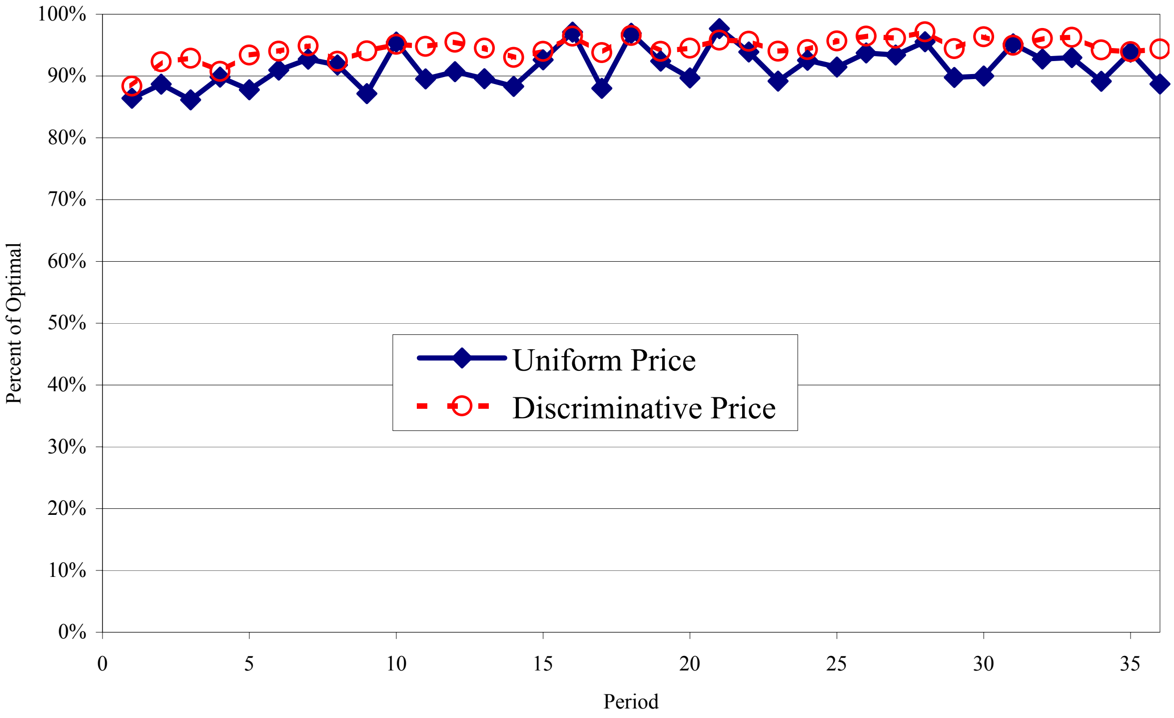


**Figure 5A: Average Seller Profits, by Treatment for Each Period (Nitrogen Environment)**

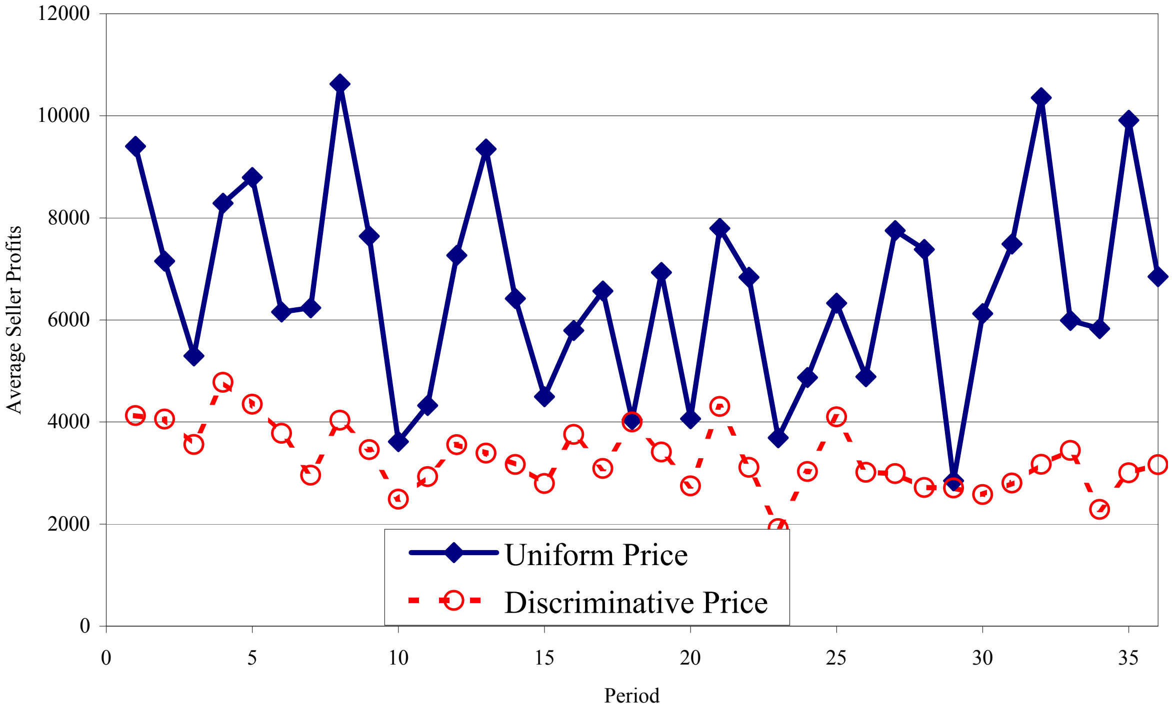
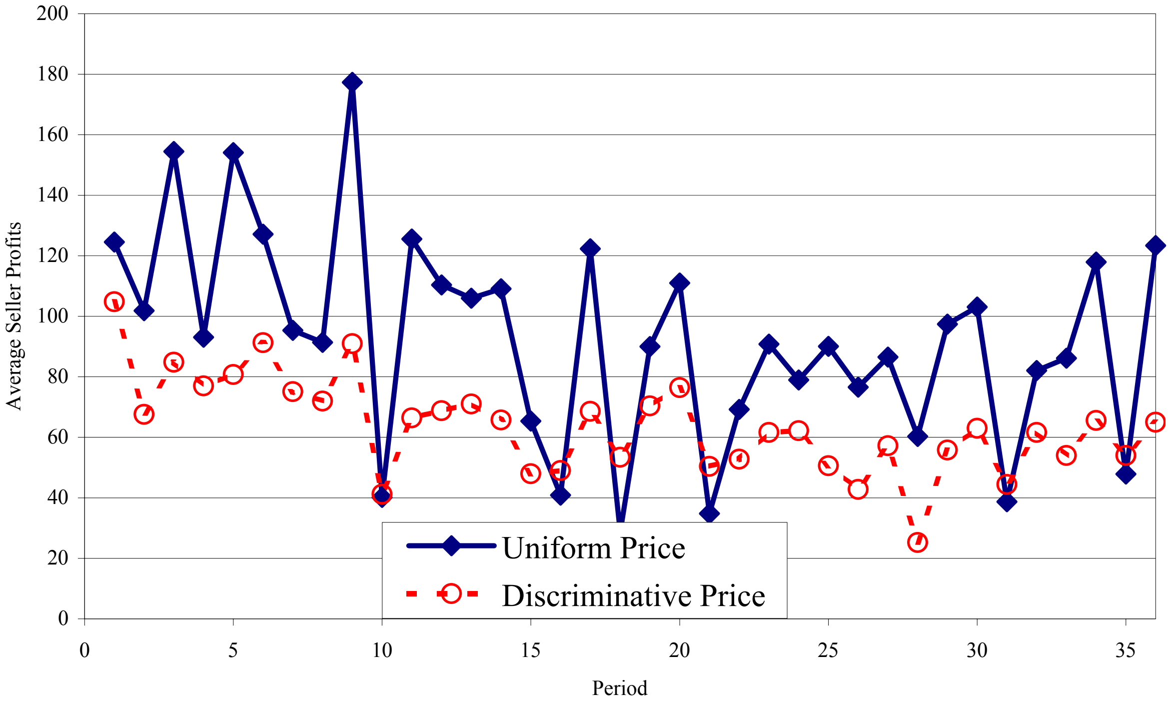
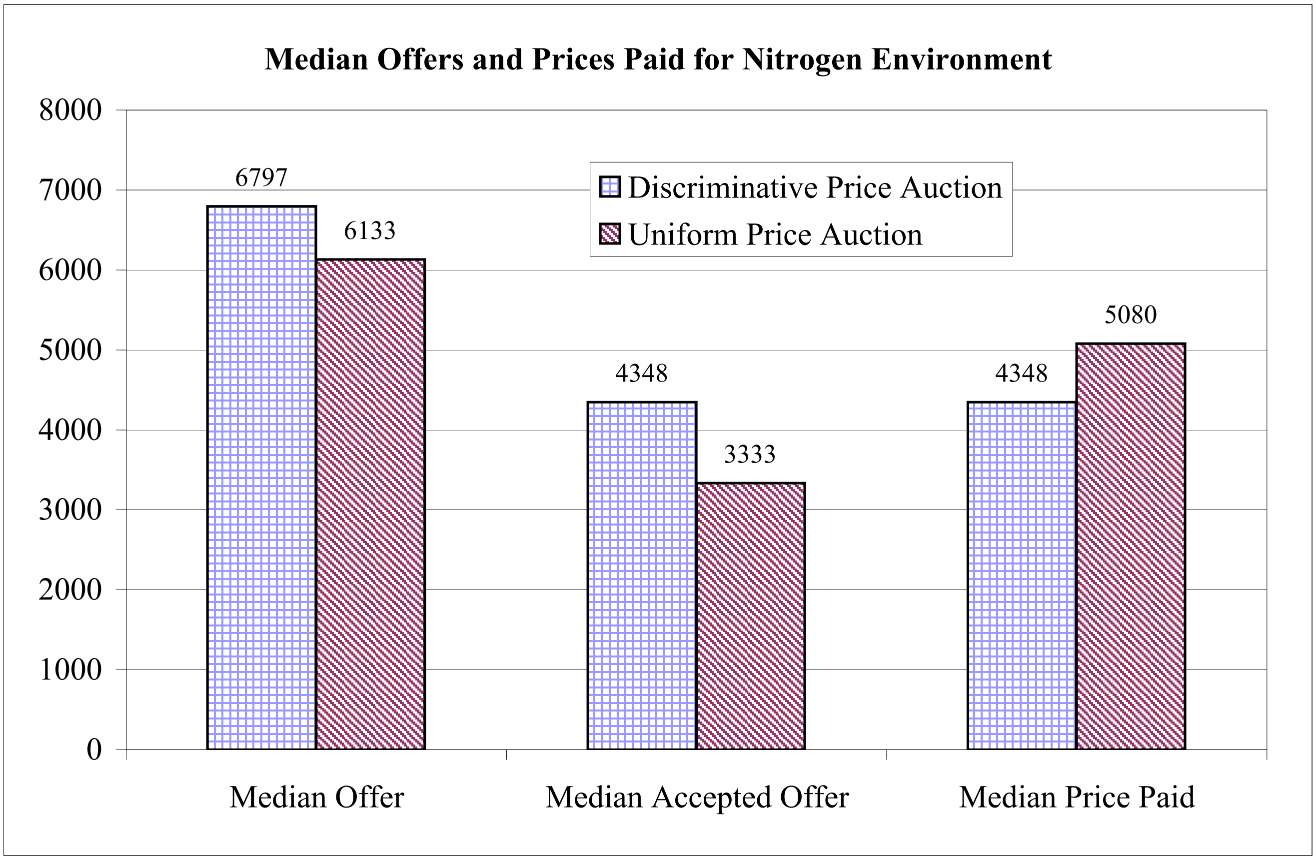
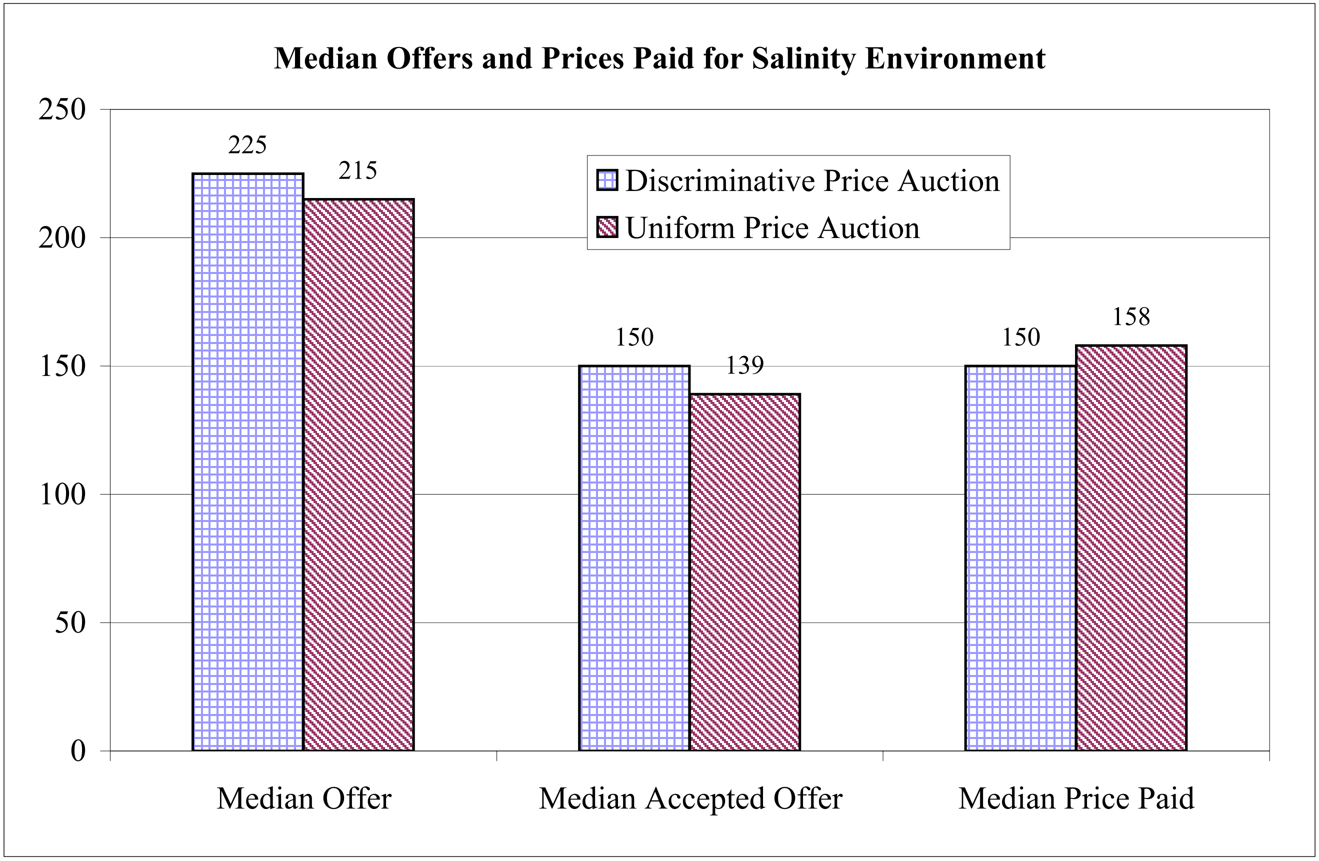


**Figure 5B: Average Seller Profits, by Treatment for Each Period (Salinity Environment)**



## Figure 6: Median Offers and Prices Paid


Median Offers and Prices Paid for Nitrogen Environment


Median Offers and Prices Paid for Salinity Environment