AUCTION SCOPE, SCALE AND PRICING FORMAT
Agent-based Simulation of the Performance of a Water Quality Tender

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Abstract: Conservation auctions are tender-based mechanisms for allocating contracts among landholders who are intertested in undertaking conservation activities in return for monetary rewards. These auctions have grown in popularity over the last decade. However, the services offered under these auctions can be complex and auction design and implementation features need to be carefully considered if these auctions are to perform well. Computational experiments are key to bed-testing auction design as the bulk of auction theory (as the rest of economic theory) is focused on simple auctions for tractability reasons. This paper presents results from an agent-based modelling study investigating the impact on performance of four auction features: scope of conservation activities in tendered projects; auction budget levels relative to bidder population size (scale effects); endogeneity of bidder participation; and auction pricing rules (uniform versus discriminatory pricing). The results highlight the importance of a careful consideration of scale and scope issues and that policymakers need to consider alternatives to currently used pay-as-bid or discriminatory pricing fromats. Averaging over scope variations, the uniform auction can deliver at least 25% more benefits than the discriminatory auction.

1 INTRODUCTION

This article presents results from an agent-based modelling study undertaken as a component of federally-funded auction trial project undertaken in Queensland, Australia. The trial known as the Lower Burdekin Dry Tropics Water Quality Improvement Tender Project was developed with the aim of exploring issues of scope and scale in tender design (Rolfe et al., 2007). It involved the conducting of a trial auction, an experimental workshop and this agent-based modelling (or computational experiments) component. The objectives of the project were to assess whether and how increases in scale and scope of a tender may lead to efficiency gains and investigate the extent to which these gains might be offset as a result of higher transaction costs and/or lower participation rates.

Auctions exploit differences in opportunity costs. Therefore, one would expect budgetary efficiency to be enhanced if tenders have wider scale and scope. However, auctions with wider coverage might involve complex design as well as higher implementation costs. Auctions with wider scope might also attract lower participation rates. An evaluation of these trade-offs is essential to the proper design of conservation auctions.

The agent-based modelling study presented here focused on evaluating the impact of auction scale and scope changes in the presence of bidder learning. The study also explored the impact on performance of the use of an alternative auction pricing format, namely, uniform pricing, which pays winners the same amount for the same environmental benefit. These auction design features are evaluated, first, by ignoring the possible ramifications of auction outcomes on the tendency to participate and, second, by

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allowing bidder participation to be affected by tender experience.In summary, the agent-based modelling study simulated aucton environments and design features that could not be explored through the field trials.

The paper is organized as follows. The next section presents the case for agent-based modelling in the design of auctions. Agent-based computational approaches are being increasingly utilized in the economics literature to complement analytical and human-experimental approaches (Epstein and Axtell, 1996; Tesfatsion, 2002). The distinguishing feature of agent-based modelling is that it is based on experimentation or simulation in a computational environment using an artificial society of agents that emulate the behaviours of the economic agents in the system being studied (Tesfatsion, 2002). These features make the technique a convenient tool in contexts where analytical solutions are intractable and the researcher has to resort to simulation and/or in contexts where modelling outcomes need to be enriched through the incorporation of agent heterogeneity, agent interactions, inductive learning, or other features. Section 3 presents the auction design features explored in the study. These include budget levels, scope of conservation activities, endoegeneity of participation levels, and two alternative pricing formats. Simulated results are presented and discussed in Section 4. The final section summarizes the study and draws conclusions.

2 AGENT-BASED AUCTION MODEL

Auction theory has focused on optimal auction design, but its results are usually valid only under very restrictive assumptions on the auction environment and the rationality of the players. Theoretical analysis rarely incorporates computational limitations, of either the mechanisms or the agents (Arifovic and Ledyard, 2002). Experimental results (Erev and Roth, 1998; Camerer, 2003) demonstrate that the way people play is better captured by learning models rather than by the Nash-Equilibrium predictions of economic theory. So, in practice, what we would observe is people learning over time, not people landing on the Nash equilibrium at the outset of the game. The need to use alternative methods to generate the outcomes of the learning processes has led to an increasing use of human experimental as well as computational approaches such as agent-based modelling.

Our agent-based model has two types of agents representing the players in a procurement auction, namely one buyer (the government) and multiple sellers (landholders) competing to sell conservation services. Each landholder has an opportunity cost that is private knowledge. The procuring agency or government agent has a conservation budget that determines the number of environmental service contracts.

Each simulated auction round involves the following three major steps. First, landholder agents formulate and submit their bids. Second, the government agent ranks the submitted bids based on their environmental benefit score to cost ratios and selects winning bids. The number of successful bids depends on the size of the budget and the auction price format. In the case of discriminatory or pay-as-bid pricing, the government agent allocates the money starting with the highest ranked bidder until the budget is exhausted. In a uniform pricing auction, all winning bidders are paid the same amount per environmental benefit. The cutoff point (marginal winner) for this auction is determined by searching for the bid price that would exhaust the budget if all equally and better ranked bids are awarded contracts. Third, landholder agents apply learning algorithms that take into account auction outcomes to update their bids for the next round. In the very initial rounds, these bids are truthful. In subsequent rounds, these bids might be truthful or involve mark-ups over and above opportunity costs.

Bids are updated through learning. Different learning models have been developed over the last several decades and can inform simulated agent behaviour in the model. A typology of learning models presented by (Camerer, 2003) shows the relationship between these learning algorithms. This model combines two types of learning models: a direction learning model (Hailu and Schilizzi, 2004; Hailu and Schilizzi, 2005) and a reinforcement learning algorithm (Hailu and Thoyer, 2006; Hailu and Thoyer, 2007). These two algorithms are attractive for modelling bid adjustment because they do not require that the bidder know the forgone payoffs for alternative strategies (or bid levels) that they did not utilize in previous bids.

Learning direction theory asserts that ex-post rationality is the strongest influence on adaptive behaviour (Selten and Stoecker, 1986; Selten et al., 2001). According to this theory, more frequently than randomly, expected behavioural changes, if they occur, are oriented towards additional payoffs that might have been gained by other actions. For example, a successful bidder, who changes a bid, is likely to increase subsequent bid levels. Reinforcement learning (Roth and Erev, 1995; Erev and Roth, 1998) does not impose a direction on behaviour but is based on the reinforcement principle that is widely accepted in the psychology literature. An agent's tendency to select a strategy or bid level is strengthened (reinforced) or weakened depending upon whether or not the action results in favourable (profitable) outcomes. This algorithms also allows for experimentation (or generalization) with alternative strategies. For example, a bid level becomes more attractive if similar (or neighbouring) bid levels are found to be attractive.

In our model, we combine the two learning theories because it is reasonable to assume that direction learning is a reasonable model of what a bidder would do in the early stages of participation in auctions. These early rounds can be viewed as discovery rounds where the bidders, through their experience in the auctions, discover their relative standing in the population of participants. It would thus be reasonable to assume that successful bidders would probabilistically adjust their bids up or leave them unchanged. However, this process of directional adjustment would end once the bidder fails to win in an auction. At this stage, the bid discovery phase can be considered to have finished and the bidder to be in a bid refinement phase where they chose among bid levels through reinforcement algorithm, with the probability or propensity of choice initially concentrated around the last successful bids utilized in the discovery phase. Further details on the attributes and implementation of the reinforcement algorithm are provided in the paper by Hailu and Thoyer on multi-unit auction pricing formats (Hailu and Thoyer, 2007).

3 DESIGN OF EXPERIMENTS

In all experiments reported in this paper, a population of 100 bidding agents is used. This number is chosen to be close to the the number of actual bids (88) submitted in the Burdekin auction trial (Greiner et al., 2008). The opportunity cost of these bidding agents depend on the mix of water quality enhancing activities that are included in their projects. This dependence of opportunity cost on project activities is determined based on the relationship between costs and activities implied in the actual bids. A data envelopment analysis (DEA) frontier is constructed from the actual bids to provide a mechanism for generating project activities that extrapolate those observed in the actual trial. For a given bundle of conservation activities, this frontier provides the best possible cost estimate. This cost estimate is then adjusted by a random draw from the cost efficiency estimates obtained for the actual bids.

The nature of the bidder opportunity costs, the budget, payment formats and the responses of bidder agents to auction outcomes are varied so that results are generated for experiments that combine these features in different configurations. Further details on these design variations are provided below.

3.1 Scope of Conservation Activities

Changes in scope of the auction are imitated through variations in the coverage of water quality improving activities undertaken by the bidding population. These activities are nitrogen reduction, pesticide reduction and sediment reduction. In the actual bids, the sediment reducing projects came almost entirely from pastoralists while the nitrogen and pesticide reducing activities came from sugar cane growers. The shares of nutrient, pesticide and sediment reduction in the environmental benefits (EBS) score value were varied between 0 and 1 to generate a mix of activities covering a wide range of heterogeneity in projects. For example, to simulate auction performance for a case where the range of allowed activities is on average a 50/50 contribution from nitrogen and pesticide reducing activities, a random population of 100 shares is drawn from a Dirichlet distribution centered at (0.5,0.5). This is then translated into nitrogen, pesticide and sediment quantities using the relationship between environmental benefit scores and reduction activities employed for the actual auction[1].

3.2 Auction Budgets

Two auction budgets are used, $600K and $300K. The first level represents approximately the actual budget used in the field trials, while the second budget indicates a higher level of competition or "degree of rationing" that can be achieved by increasing the scale of participation.

3.3 Endogeneity of Bidder Participation

Auction performance is likely to be influenced by the dynamics of participation. Unless auctions are organized differently (e.g. involving payments that maintain participation levels), one would expect some of the bidders to drop out as a result of failure to win contracts. Therefore, we carry out computational experiments for a case where bidders are assumed to participate even in the case of failure and also for a case where bidders drop out, with some probability.

[1]The method used is an approximation to the actual procedure based on a regression of reduction activity levels and EBS scores. This was done because the actual scoring involved adjustments that credited projects with extra points for other aspects of the project besides nitrogen, pesticide or sediment reduction.

In the second case, if a bidder fails to win contracts, the probability of dropping out increases up to a maximum of 0.5. However, a simulation that allows for a one-way traffic (i.e. exit) would not take into account the fact that the auction can become more attractive as bidders drop out and competition declines. Therefore, we allow for both exit and re-entry into the auctions. Re-entry by inactive bidders occurs with a probability that is increasing with the average net profit participating bidders are making from their contracts.

3.4 Auction Price Format

The choice of payment formats has been an interesting research topic in auction theory. Theory offers guidance on choices in simple cases but has difficulty ranking formats in more complex cases, whether the complexity arises from the nature of the bidder population or the nature of the auction (e.g. multi-unit auction (Hailu and Thoyer, 2007)). The Burdekin field trial, like most Market-based instrument (MBI) trials conducted to date, has used a pay-as-bid or discriminatory pricing format. In the agent-based simulations, this payment format is compared to the alternative format of uniform pricing where winning bidders would be paid the same per unit of environmental benefit.

The auction design features discussed above are varied to generate and simulate a range of auction market experiments. Each auction experiment is replicated 50 times to average over stochastic elements involved in the generation of opportunity cost estimates and the probabilistic bid choices that are employed in the learning algorithms. Results reported below are averages over those 50 replications.

4 AUCTION PERFORMANCE

The key finding from these experiments is that outcomes vary greatly with the details of the auction and the activities covered in its scope. The results are summarized below.

4.1 Scope Effects

The performance of the auction as measured by benefits per dollar spent is dependent on the scope of conservation activities that are eligible. The benefits per dollar range from a low of 1.91 environmental benefit scores (EBS) per million dollars to a high of 3.62. An increase in the share of sediment reduction reduces benefits obtained; the benefits per million dollars are always less than 3.0 when there is a positive average share of sediment reduction activities. The benefits improve with improvements in the share of pesticide reduction activities.

In Figure 1, the benefits are plotted against the average shares of nitrogen and pesticide contribution to water quality in the projects. The horizontal axis in the figure indicates the relative contribution of nitrogen reduction while the y-axis (diagonal line) indicates the share of pesticide. The residual contribution is the share of sediment reduction. Points at the bottom-right corner have higher shares of nitrogen as opposed to points closer to the top-left corner of the diagram. Points on the top-left to bottom-right diagonal line correspond to a constant combined contribution from nitrogen and pesticide reduction (i.e. they represent a constant sediment contribution). Therefore, points further to the left of the diagonal line stretching from the top-left hand corner to the right-bottom corner include higher shares of sediment reduction. The dots in the figure show the deterioration in benefits per dollar as the scope of the auction covers more and more sediment reduction. Looking at variations other than sediments, the changes in the heights of the lines increasing towards the top-left corner (from the bottom-right) indicate the increase in benefits that occur as the share of pesticide increase at the expense of nitrogen reduction with sediment reduction excluded. See Table 3 in the Appendix for further details on the results.

4.2 Budget Levels and Auction Efficiency

For a discriminatory auction with 100 bidders, halving the budget from \$600,000 to \$300,000 has a large effect on the performance of the auction. The benefit to cost ratios are more than 50% higher for the auction with the \$300,000 budget. See Figure 2 where the benefits per million dollars for the auction with the two budgets are shown. The different points represent results for the different mixes in activities discussed above. All the points fall between the two dotted lines which represent ratios of 2 and 1.5 between the values on the y and x axes.

The benefits of the higher degree of rationing are similarly strong for all other experiments where other features of the auction are varied (e.g. pricing formats). Considering all cases together, the benefits per dollar from the auction with a budget of \$300,000 can be between 40 and 100% above those where the budget is \$600,000. On average, the benefits were 67% higher. The benefits of the higher degree of rationing (or increased competition for a given budget) are notably higher when the scope of the auction is such that

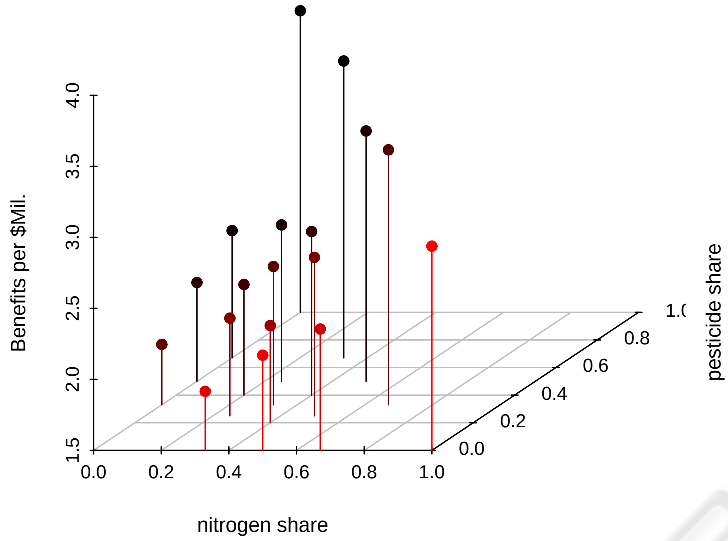

Figure 1: Conservation activity mix and auction performance.

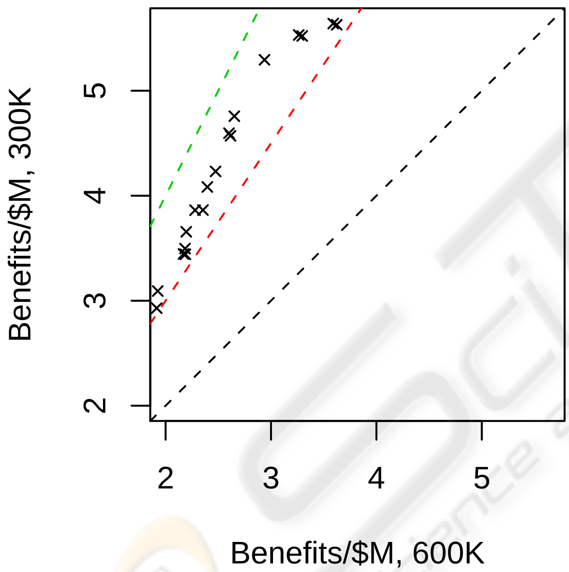

Figure 2: Benefits per million dollar for auctions with budgets of $300,000 and $600,000.

it covers higher cost activities.

4.3 Participation and Efficiency

Results for repeated auctions where bidders stay active even after bids are unsuccessful are only marginally higher than for cases where bidders drop out (and re-enter). The weakness of these results seems to be due to the way the participation rules are formulated in the simulation, being biased in favour of bidding. For example, in our experiments, a bidder who just lost in an auction might participate in the next one with a probability of at least 0.5 depending on their net revenue from the contracts in previous rounds. In practice, bidders might be more responsive to bid failures and the results reported here would understate the importance of investments in landholder participation.

4.4 Uniform versus Discriminatory Pricing

Results for a uniform pricing format where every winning bidder gets paid the same for the same environmental benefit are generated and compared with those obtained under simulation conducted for discriminatory pricing. The key results are summarized in Table 1 where we report the ratios of values from the uniform price auction to those from the discriminatory price auction for both budget levels and activity threshold specifications. A ”yes” value for activity threshold or endogenous participation indicates that the results in the row are for simulation where bidders drop out as a result of failure to win. Each row reports the results for the corresponding budget and activity threshold averaged over all the activity scope variations covered in the experiments.

In terms of performance, the results reported in the third column indicate that a uniform auction delivers benefits that are at least 25% higher than those obtained under a discriminatory auction when performance measures are averaged over all scope variations. The relative benefits of the uniform auction are highest when competition is tight (budget of

Table 1: Ratio of results from uniform auction to those from discriminatory auction.

Budget (000s)	Endogeneous participation	Ratio of benefits per dollar	Ratio of first ranked bid price	Ratio of last ranked bid price
300	no	1.30	0.52	0.45
300	yes	1.36	0.49	0.37
600	no	1.25	0.29	0.51
600	yes	1.28	0.28	0.43

$300,000) and for the case where bidders tend to drop out when they fail to win contracts.

The higher benefits obtained under the uniform price auction are the result of the fact that it encourages less overbidding than the discriminatory pricing auction. This can be seen in the last two columns of Table 1 where the figures indicate the ratios of the bid prices from uniform to those from discriminatory prices for the highest (column 4) and for the lowest ranked (column 5) bidders in the auction. The first row results show that the benefit price (bid to benefit ratio) of the highest ranked and the lowest ranked bidders under the uniform auction were only 52 and 45 percent of the corresponding figures for the discriminatory auction. In other words, the bids under the uniform auction are more truthful or involve less overbidding. This is because the bidder does not have the incentive (unless they are the marginal bidder) to misrepresent their bid under the uniform auction; subject to winning, a bidder's payoff does not depend on their own bid but on that of the most expensive winner. The disparity between the bids of the best ranked bidders are highest for the higher budget auction.

In summary, the performance of the auction is dependent on the variations considered in the computation experiments. To investigate the individual contributions of the different auction features, the benefits per dollar are regressed against variables representing the design features. These results are presented in Table 2 which highlights the importance of the auction design features, with 93% of the benefit per dollar variations explained by the design features. Increases in budgets (for a given pool of bidders), share of sediment reduction contribution, discriminatory pricing and the presence of activity threshold in a bidders decision to participate all contribute towards lower benefit value per dollar spent. Higher shares for pesticide reduction activities, on the other hand, increase efficiency.

5 CONCLUSIONS

This study conducted computational experiments to evaluate the impact on auction performance of several design features, including: the scope of water quality improving activities allowed in projects; the scale of the auction as measured by the budget size relative to participating bidder numbers; and the choice of pricing format. These design features were conducted for two cases of bidder responses to failures in auctions. In the first case, bidder numbers were assumed to be constant regardless of auction outcomes. In the second case, bidders were assumed to drop out with a probability if they lose in tenders and to re-enter in with a probability that increases with the net revenue from contracting that is obtained by active bidders.

The results consistently indicate that auction performance as measured by environmental benefits per dollar is highly dependent on the mix of conservation activities allowed in the projects. In particular, increases in the average share of sediment reduction activities are detrimental to the performance of the auction. The environmental benefits generated per dollar of funding fall consistently as the average share of sediment reduction activities in projects rises. This outcome is a reflection of the more costly nature of sediment based activities and highlights the need for the identification of scope/efficiency trade-offs based on the nature of conservation activities that prevail in different industries. It demonstrates that narrowly scoped auction focused on activities with high opportunity costs can perform very poorly compared to more broadly scoped auctions.

Improvements in the scale of participation are highly beneficial for auction performance. The benefits of a higher degree of rationing obtained through higher participation numbers relative to budgets are very strong. In this case study, the benefits per dollar from the auction with a budget of $300,000 can be between 40 and 100% above those where the budget is $600,000. The benefits of the higher degree of rationing or increased competition for a given budget are notably higher when the scope of the auction is such that it covers higher cost activities.

Results for repeated auctions where bidders stay active even after bids are unsuccessful are only marginally higher than for cases where bidders drop out and re-enter. The weakness of these results seems to be due to the way the participation rules are formulated in the simulation as discussed. Bidders might be

Table 2: Results from a regression of environmental benefits per dollar on auction design features.

Variable	Coef. estimate	t-stat
(Intercept)	0.00811	60.987
Share of Pesticide	0.00057	4.309
Share of Sediment	-0.00322	-20.727
Budget (dummy, with 600K equal to 1)	-0.00001	-31.243
Discriminatory pricing (dummy)	-0.00101	-16.253
Activity threshold (dummy, 0 if bidders do not drop out)	-0.00007	-1.169
R-squared	0.93	

more responsive to bid failures than is assumed in the simulations.

Finally, the use of uniform pricing rather than discriminatory pricing in repeated auctions would lead to higher benefits per conservation dollar. With uniform pricing, bidders get paid the price of the marginal winner. Their own bids influence whether they win or not but not how much they get paid (unless they are the most expensive winner). This auction leads to more truthful bidding or to less overbidding. The simulations indicate that with uniform pricing in repeated auctions, one could increase the benefits per dollar by between 15 and 55%. The benefits from uniform pricing are especially higher if bidders tend to drop out following bid failures.

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APPENDIX

Table 3: Benefits per million dollars for alternative activity scopes.

Nitrogen share	Pesticide share	Sediment share	Benefits per Mill. $
0.00	1.00	0.00	3.62
0.00	0.50	0.50	2.20
0.00	0.33	0.67	1.93
0.00	0.67	0.33	2.40
1.00	0.00	0.00	2.94
0.50	0.00	0.50	2.17
0.33	0.00	0.67	1.92
0.50	0.50	0.00	3.26
0.33	0.33	0.33	2.47
0.25	0.25	0.50	2.19
0.33	0.67	0.00	3.59
0.25	0.50	0.25	2.60
0.20	0.40	0.40	2.28
0.67	0.00	0.33	2.35
0.67	0.33	0.00	3.30
0.50	0.25	0.25	2.62
0.40	0.20	0.40	2.18
0.40	0.40	0.20	2.65