Bilateral Negotiations versus a Clearinghouse Market for Water Quality Trading

A stochastic agent-based modeling approach

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Abstract

The efficiency of emissions trading in bilateral exchange and clearinghouse markets with heterogeneous, boundedly rational agents making decisions under imperfect and asymmetric information, as well as transaction costs is examined. Results are derived using stochastic agent-based simulation models of agents' decision-making and interactions. The stochastic agent-based models are designed to simulate the outcomes of trading within a set of trading rules, market structure, and agent information structures consistent with emerging water quality trading programs. In essence, two versions of a stochastic agent-based simulation model are developed, one with bilateral negotiations being the coordination mechanism and the other with a clearinghouse. The Differential Evolution algorithm is used to search for market trade strategies that perform well under multiple states of the world. The analysis is designed to provide a strong test of trading efficiency within each market structure and allows a comparison of market outcomes between the two market structures. The effects of trade policy parameters and transaction costs on market outcomes are also examined. The findings show that the clearinghouse market is performing better than the bilateral negotiation mechanism in various efficiency measures. Both market structures face a high probability of failing to attain the least-cost solution to the social planner's problem. However, the clearinghouse market structure appears to approximate the least-cost solution better than the bilateral negotiation mechanism when ignoring the public costs of establishing the clearinghouse.

Key words: agent-based model, bilateral negotiations, clearinghouse, water quality trading, asymmetric information, transaction costs and Differential Evolution algorithm.

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1. Introduction

Water quality trading is being promoted by the US Environmental Protection Agency (EPA) and explored by several states as a means for achieving water quality goals, especially within the context of EPA's Total Maximum Daily Load program. Water quality trading is fundamentally a decentralized mechanism for allocating, as required by the Total Maximum Daily Load program, pollution loads among alternative sources consistent with an overall pollution load target. The heightened interest in water quality trading lies in the fact that market transactions can achieve pollution targets cost effectively in markets that environmental regulators can construct without knowing the polluters' abatement costs (Crocker 1966, Dales 1968, Montgomery 1972). This capacity makes water quality trading economically appealing compared to traditional regulatory tools.

A major challenge to the success of water quality trading is to control agricultural nonpoint sources. Agricultural nonpoint sources are the leading cause of remaining water quality problems and must be controlled if water quality objectives are to be achieved in many watersheds. Yet, the very character of nonpoint pollution, unobservable, inherently stochastic and spatially dependent, greatly complicates the design of markets. In particular, an optimally designed water quality trading framework that includes nonpoint sources will differ significantly from the 'textbook' model that underpins the success of large scale national air pollution trading programs (Horan and Shortle 2011). The textbook vision requires that emissions (i) can be accurately metered for each regulated emitter, (ii) are substantially under the control of the polluter, (iii) do not spatially affect environmental outcomes and (iv) that the market is perfectly competitive (Ellerman 2005). Nonpoint emissions do not satisfy the first three requirements due to their inherent characteristics. Moreover, perfectly competitive markets do not represent the realities of actual water quality trading markets that have been developed to date. Perfectly competitive markets require a large number of traders, all with perfect information but none with market power, trading a homogeneous good. Regulation of water pollution at small spatial scales (e.g., stream segments, small watersheds) will often imply "markets" with limited numbers of potential participants. Traders can be highly heterogeneous in their economic activity, economic size, and contribution to pollution loads. For example, likely participants in a point-nonpoint nutrient trading market could range from small farms to large treatment works. Further, polluting emission even within a specific category (e.g., nitrogen) can be highly heterogeneous in water quality relevant characteristics (e.g., nitrogen type, time and place of release, etc.). These characteristics eliminate the development of highly organized competitive exchange markets in which traders routinely participate as price taking buyers or sellers. The performance of water quality trading markets must, therefore, be understood within the context of market structures that are plausible for the problem.

Bilateral negotiations and clearinghouse market structures are the most common mechanisms of exchange in actual point-nonpoint water quality trading markets in the United States and elsewhere (Morgan and Wolverton 2005; Selman et al. 2009). In these market structures, the assumptions about individual behavior, information structures and coordination mechanisms deviate from those inherent in perfectly competitive markets (Woodward et al. 2002). Existing empirical economic models of trading typically do not model individual agent behavior in markets because they assume that markets are perfectly competitive and will achieve the least-cost allocation in equilibrium (Horan et al. 2002, Tietenberg 2006). Under this assumption market equilibrium is computed by solving a cost-minimization problem. The approach in existing water quality trading literature cannot be used to explore the efficiency of water quality markets because it is based on the assumption that markets are efficient.

Nguyen et al. (2010) demonstrated through a stochastic agent-based simulation model of point-nonpoint trading that bilateral trading markets are unlikely to achieve or even approximate least-cost allocations under uncertainty and transaction costs. Indeed, their findings showed that the market organized by bilateral negotiations has a high probability of failing to attain its least-cost solution given alternative specifications of market design parameters. The existence of positive gains from trade relative to the Autarky solution (no trading) is only a necessary but not a sufficient condition that warrants the achievement of the least-cost solution to the planner's problem. Expectations of gains from water quality trading, therefore, should be tempered. Furthermore, the fact that the market fails to achieve the least cost solution through bilateral trading might have to do with the negotiation mechanism. A mechanism that enhances coordination among market participants in trading such as a clearinghouse should be considered.

In this paper, we extend on Nguyen et al. (2010) and examine the efficiency of the clearinghouse market mechanism. As a result, it is possible to compare the performances of both bilateral negotiation and clearinghouse market mechanisms in achieving the environmental target cost effectively. While it is commonly known that, ignoring the public costs of establishing the market, a clearinghouse market is likely to be more efficient than a bilateral negotiation framework, the validity of such an expectation is worth examining in the case of water quality trading. In addition, the impacts of two key market design parameters on market outcomes and efficiency are examined for each of the market structures. The two trade policy parameters are (i) the uncertainty trading ratios, used to address the relative uncertainty of nonpoint pollution reductions and (ii) the stringency of the required pollution reduction or the environmental target.

A stochastic agent-based modeling framework is designed to simulate the outcomes of trading within a set of trading rules and market structures consistent with developing US markets for nutrient trading between point and nonpoint sources (Morgan and Wolverton 2005; Selman et al. 2009). In essence, two versions of a stochastic agent-based simulation model are developed, one version with bilateral negotiations being the coordination mechanism and the other with a clearinghouse. The stochastic agent-based models allow the assumption of perfect competition to be replaced by more realistic assumptions about individual behavior, information structure and coordination mechanism. In particular, agents are assumed to have imperfect information about their own costs and the costs of others. They are modeled as boundedly rational and thus using simple but plausible heuristics in decision making. Within this context, a strong test of trading efficiency is constructed that entails creating and evaluating a large sample of market outcomes. The outcomes of both the bilateral and clearinghouse markets are evaluated using the Differential Evolution algorithm (Storn and Price 1997) which searches for market trade strategies that perform well in terms of minimizing the expected total cost of pollution control for the whole watershed under multiple uncertain states of the world (reflecting economic parameter variations). The resulting market outcomes are not viewed as predictions of market equilibria. This is because the underlying strategies are selected by a mechanism, the Differential Evolution algorithm, which is not available to the decentralized market. It is noted that the stochastic agent-based model is formulated to capture only the lower bound complexity expected in actual water quality trading markets. The lower bound complexity case should maximize the potential for water quality trading markets to attain their theoretical potential. The agent based approach stands in contrast to the common use of cost-minimization models for *ex ante* analysis of pollution trading, which assume that markets are perfectly competitive and will achieve the least-cost allocation in equilibrium (Hanley et al. 2007).

The findings show that the clearinghouse market is performing better than the bilateral negotiation mechanism in achieving gains from trades. Larger trade volumes and higher level of abatement required by the pollution load target are achieved through trading. In the clearinghouse market, the presence of the auctioneer eliminates the uncertainty of trading partner selection and matching faced by the buyers in bilateral negotiations, therefore, participation does not need to be as high as in bilateral trading mechanism. Similar to findings in Nguyen et al. (2010), both bilateral trading and the clearinghouse market face high probability of failing to attain its least-cost solution. However, the clearinghouse market structure appears to approximate the least-cost solution better than the bilateral negotiation mechanism when ignoring the public costs of establishing the clearinghouse.

In section 2, the conceptual framework of the agent-based credit trading model is presented. Section 3 provides a description of the efficiency test for both bilateral trading and trading in the clearinghouse market structure. The details of the simulation and computational experiments are given in Section 4. Sections 5 and 6 present results, findings and concluding comments.

2. An Agent-based Conceptual Framework of Credit Trading

As outlined in Nguyen et al. (2010), this research models an emissions credit trading program between point sources and nonpoint sources consistent with EPA trading policy guidelines and existing US nutrient point-nonpoint pollution trading programs (Morgan and Wolverton 2005; Ribaudo and Gottlieb 2011; US EPA 2003; 2007). These programs are typically designed to achieve a pollution load limit, usually in the form of a Total Maximum Daily Load, for a specific watershed. Agriculture is the leading nonpoint source participant in nutrient programs. Unlike textbook cap-and-trade models, US water quality trading programs that include agricultural and other nonpoint sources are only partially capped (Shabman and Stephenson 2007). These programs allow trading between point sources that are subject to explicit regulatory limits and nonpoint sources that are not. They allow point sources to use emissions reduction credits produced voluntarily by agricultural sources to offset point source emissions as a means for complying with the point sources' emissions limits. Trading rules are typically designed with the intent that offsets produce a net reduction in total pollution. US nutrient water quality trading programs essentially create profit-making opportunities for agricultural sources that can reduce nonpoint source pollution, but do not in fact cap agricultural nonpoint pollution.

2.1 Trading Rules

Consider a trading program for which there are m eligible point source participants (e.g., publicly owned sewage treatment plants) and n eligible nonpoint source participants (e.g., farms), with the set of point sources denoted by $i = 1$ to m, and the set of nonpoint sources $j = 1$ to n. Each point source i is subject to an individual discharge limit r_i analogous to a water quality based effluent limit (WQBEL) in the National Pollutant Discharge Elimination System (NPDES)[2]. A point source can satisfy its regulatory requirement by reducing its own emissions or through emissions reduction credits acquired from nonpoint sources. The point source restrictions are set to achieve a specified limit on the total pollution load measured a given location (e.g., the mouth of the watershed) which we refer to as the receptor. Nonpoint sources earn emissions reduction credits by implementing pollution control practices (e.g., Best Management Practices). Rules established by the water quality agency specify the number of credits associated with the implementation of any allowable best management practice. These rules indicate the expected average annual emissions reduction from the farm. A nonpoint source j, who achieves an estimated abatement of μ_j can sell up to cr_j credits (quantified at the receptor)[3].

Imperfect substitution between point and nonpoint source emissions reductions is addressed in water quality trading programs by the application of uncertainty trading ratios that specify the minimum number of nonpoint source credits that are required to offset a unit of point source emissions (USEPA 2003; 2007). Uncertainty trade ratios almost always exceed 1:1, indicating the more than one nonpoint source credit is required to offset one unit of point source emission. We denote the uncertainty trade ratio as t and conduct experiments to explore how the choice of the ratio affects the structure and efficiency of trading. Trade ratios are also commonly used to adjust for imperfect substitution between pollution sources related to differences in the impacts of emissions on the ambient water quality due to differences in the location of emissions. Trade ratios used for this purpose are typically constructed from *delivery* or *attenuation ratios* (USEPA 2003; 2007). Let δ_i and δ_j be the proportions of the emissions from a point

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[2] US point source discharge permits impose technology-based effluent limits (TBELs) on all regulated point sources. They may also impose additional limits, referred to as water quality based effluent limits (WQBELs), if required to meet in-stream water quality standards. National water quality regulations do not allow the use of offsets to meet TBELs but will allow them to meet WQBELs.

[3] The nonpoint sources are sometimes required to meet "baseline requirements" before being able to generate credits for sale. The baseline requirements are established by the regulatory authority. In the US context, the baselines for all nonpoint sources can be chosen to be load allocation (where a TMDL exists), state or local requirements or existing practices and that any pollution reduction below their current level will be qualified as credits (Kibler and Kasturi 2007; US EPA 2007).

source and a nonpoint source, respectively, which are actually delivered to the receptor from a particular location in the watershed.

The amount of abatement reduction required, $\hat{a}_i$, by a point source at the point of discharge to fulfill the obligation of reducing r_i units of emissions at the receptor is given by:

Equation 1

$$\hat{a}_i = \frac{r_i}{\delta_i}$$

where $\boldsymbol{\delta_i} \in (\mathbf{0}, \mathbf{1}]$. This requirement can be met through emission reductions by the source and/or by purchasing credits from one or more nonpoint sources. The number of credits from source *j* required by to offset a unit of emissions from source *i* is given by

Equation 2

$$cr_j = \frac{t * \mu_j}{\delta_j}$$

where $\boldsymbol{\delta_j} \in (\mathbf{0}, \mathbf{1}]$.

2.2 Negotiation Models: Bilateral Negotiations versus Clearinghouse Market

Pollution credit transactions are modeled to occur through two different negotiation protocols. Bilateral trading and clearinghouse market are the most common mechanisms found in existing water quality trading markets (Morgan and Wolverton 2005; Woodward and Kaiser 2002). In a bilateral negotiation, the buyer and seller can directly make a case-by-case assessment of trades and reach a mutual agreement on the terms of trade. Although bilateral trading tends to require high per trade transactions costs, it incurs relatively low initial costs to establish the market for the regulatory bodies (Woodward and Kaiser, 2002). This private versus public cost tradeoff is reversed for the clearinghouse system. A clearinghouse trading system provides an intermediary to connect the generator of abatement credits and the user of those credits. The intermediary reduces the contracting and information costs that would be required by bilateral negotiations, hence, decreasing the transactions costs per trade faced by the traders (Woodward and Kaiser, 2002). However, the costs for establishing norms and the review and completion of trades, as well as the operation costs of the clearinghouse can be sizeable (Woodward et al., 2002). In choosing a market structure to reduce transactions costs, the regulatory bodies have to consider the private and public costs trade-off to ensure market efficiency and environmental efficacy.

In this research, nonpoint sources and point sources are assumed to have imperfect information about their own abatement costs, and the costs and bidding strategies of potential trading partners. With expenditures for information (e.g., market research, engineering consultants) agents can be better informed about some aspects of their cost structures and their trading partners', however, purchased information reduces, but does not eliminate their uncertainty. Agents are modeled to be boundedly rational, therefore, participation and trading decisions taken by agents in this model are not deterministically least-cost behaviors resulting from the solution of direct optimization problems. Decisions made are based on simple behavioral rules (Simon 1955; Epstein 1999; Thaler 1988; Tversky and Thaler 1990; Kahneman 1991) and are constrained within bounds.

Bilateral Negotiation: Ultimatum Game

As described in Nguyen et al. (2010), a relatively simple bargaining protocol analogous to an *"Ultimatum"* game is modeled (Guth et al.1982; Roth 1995; Guth 1995; Stahl and Haruvy 2008; Thaler 1988). In this one-shot bargaining game, it is assumed that point sources initiate negotiations with nonpoint sources.

A point source must first decide whether or not to participate in the market. If deciding to enter, it must register with the regulatory agency to be eligible to trade and to be able to approach potential sellers. With the registration, the point source receives a list of all registered and thus eligible participants in the market. Once the point source is registered, it may pursue trading partners and negotiate contracts.

A nonpoint source too must choose whether or not to participate. If it chooses to enter, it must also register in order to be eligible to receive offers from point sources. A participating farmer will implement pollution control practices to generate credits for sale. The decision of whether to participate in the market is made without knowing how much they will receive for credits sold. Thus, a nonpoint source must first decide whether to participate in the market (decision s_{1j}). If it decides to participate, it must select a best management practice (decision s_{2j}) with which to generate credits and determining the number of credits to sell. It must also set a reservation price for its credits.

In this game, a point source offers a bid price, P_i^{bid}, to a set of potential sellers who can either accept or reject it. Since a participating point source has already registered, it can observe the list of participating nonpoint sources. The set of candidate sellers chosen by a particular buyer, however, is a subset of the set of all participating nonpoint sources. Although each point source decides on the number of potential sellers to contact, the particular sellers to whom it sends an offer are chosen at random. This reflects part of the buyer's strategy in trying to get low price acceptances while having asymmetric information about the sellers. A nonpoint source, after receiving offers, compares the highest offered price to its own reservation price, P_j^{res} . If the highest bid price is greater than the reservation price, the nonpoint source accepts the offer and sells all the credits it has generated to this bidder when picked by the highest bidder in its list. If the highest bid price is less than the a priori formed reservation price, the nonpoint source rejects all offers.

Given the take-it or leave-it structure of bids, accepted offers can differ in the quantity of credits supplied but not in price. Accordingly, a rule is required for sorting the acceptances. We use a rule that considers the location of (i) the candidate sellers relative to the buyers and (ii) the location of candidate sellers relative to the receptor. These locations are relevant to the magnitude of transaction costs and the ambient concentration of the watershed.

Exchanges are then settled sequentially until the point source's credit demand is fulfilled or the supply of credits on offer in the acceptances is exhausted. There are no counter offers for the rejected bids. Whereas nonpoint source sellers sell only to one point source buyer, a buyer may contract with multiple nonpoint sources. This is reasonable given that an individual point source's demand is usually very large in terms of its emissions relative to an individual nonpoint source's supply. If the number of credits acquired does not cover the point source's regulatory requirement, it will have to meet the rest of its pollution abatement requirement by upgrading its treatment equipment or other internal abatement effort. If a point source can fulfill its credit demand with purchases from a subset of candidate sellers that have accepted its bid, it will not purchase credits from the entire set.

Clearinghouse Market: Discriminatory Pricing Double Auction

A discriminatory pricing double auction protocol as described in Nicolaisen et al. (2001) is adapted to the current credit trading market. The rationale for applying this clearinghouse model to point-nonpoint trading is that the matching procedure conducted by the independent auctioneer is simple and efficient. The clearinghouse/auctioneer is modeled as a non-profit entity which facilitates the functioning of the market. It is remunerated by point source and nonpoint source agents who choose to engage within the clearinghouse.

Similar to the bilateral negotiation mechanism, the nonpoint sources and point sources who decide to participate need to register with the clearinghouse to be able to submit offers or bids. At the beginning of the auction round, each participating point source submits directly to the auctioneer a bid to buy and each participating nonpoint source an offer to sell credits. The bids and offers include a price and a quantity (supplied or demanded). The clearinghouse then separately sorts the buyers and sellers by their price offers in descending and ascending orders, respectively. Matches are settled sequentially. The buyer with the highest bid price is first matched with the seller with the lowest ask price, conditional on the fact that the bid price is greater than the ask price. The midpoint of the bid-ask spread is chosen to be the unit price of the contract.

The buyer is matched with the seller for a number of permits being the smaller of the quantity demanded and supplied. If the buyer's demand is not fulfilled by trading with one seller, the remaining number of permits to buy is then calculated and the auctioneer can move to the next seller and the pair is matched in a similar fashion. In other words, a buyer can trade with multiple partners sequentially. If the supply of a seller is not fully absorbed by a buyer, then the auctioneer can match the current seller with the next buyer in the ordered list. As a result, a seller can also trade with multiple buyers sequentially.

If there is a buyer tie, i.e. two buyers offer the same bid price, the auctioneer will break the tie by comparing the distance between the two buyers to the receptor. A buyer closer to the receptor will have the priority to trade first. If there is a seller tie, i.e. two sellers offer the same price, the auctioneer will break the tie by comparing the distance between each of the sellers to the receptor. A seller closer to the receptor will have the priority to settle trades first. The rationale for choosing an agent closer to the receptor is that the environmental impact of the agent will be greater, the closer it is to the monitoring point.

2.3 Agents' Strategies

In both the bilateral negotiation and clearinghouse markets, each agent makes several decisions in its interactions with other agents. A set of decisions taken by an agent defines that agent's trade strategy. The collection of all agents' decision variables constitutes the overall market's trade strategy space.

The trade strategies for both point sources and nonpoint sources in the bilateral negotiation mechanism are described at length in Nguyen et al. (2010). To summarize, a buyer's strategy consists of four decisions: (i) whether to participate, denoted by the binary variable b_{1i}, (ii) the offer price, which is a function of the continuous real variable b_{2i}, (iii) the number of trading partners, denoted by an integer variable b_{3i}, and (iv) the trading partner matching order (i.e. with whom to finalize trades), which is a function of the distance related variable, denoted by the continuous real variable b_{4i}. A buyer's goal is to minimize the total cost of pollution control, denoted $BTCC_i$, subject to its regulatory requirement r_i and the trading rules. The total control cost post-trading for any point source *i* is given as:

Equation 3

$$BTCC_i(b_{1i}, b_{2i}, b_{3i}, b_{4i}) = BIFC_i + BCE_i + BEC_i + BDC_i + BAC_i^*$$

where $BIFC_i$ denotes information costs, BEC_i expenditures on credits, BCE_i exchange cost, BDC_i monitoring cost, and BAC_i^* abatement cost for any additional pollution reductions required beyond purchased credits or the post-trading abatement cost. The exchange and monitoring costs constitute contracting costs. Since contracting costs depend on trade volumes and locations, which are uncertain until trades have been executed, buyers in the market are uncertain about transaction costs prior to the execution of trades. Moreover, it is also assumed that a buyer does not have complete information about its own abatement cost when making trading decisions. As a result, each buyer must form an expectation of these costs. The details of these expected costs are discussed subsequently in the construction of bid prices.

A seller decides (i) whether to participate, denoted by binary variable s_{1j} and (ii) which best management practices from a discrete set of options to implement, denoted by integer decision variable s_{2j}. Associated with each best management practice is the amount of abatement that will be credited as providing at the source. This amount is determined by rules established by the water quality authority (see Section 2.1). A seller's goal is to maximize post-trading profits, denoted SP_j from their credit sales subject to the trading rules. Profit is the difference between revenues from credit sales and the costs of credit generation:

Equation 4

$$SP_j(s_{1j}, s_{2j}) = SCR_j - SIFC_j - SEC_j - SDC_j - SAC_j$$

where SCR_j denotes seller *j*'s credit revenue, $SIFC_j$ information costs, SEC_j exchange cost, SDC_j monitoring cost and SAC_j abatement costs. As with buyers, sellers do not have perfect information about their abatement costs until they have been realized. Sellers also incur contracting costs that depend on trade volumes and buyer locations, which are uncertain until trades have been executed. Thus, sellers must make decisions under uncertainty about their abatement and contracting costs. Sellers, like buyers, can acquire information on best management practice costs (e.g. from farm consultants) and its trading partners' abatement costs at a cost, $SIFC_j$. This information cost is assumed to vary with the quality of information obtained on the abatement costs of its own and its trading partners.

In the clearinghouse market, the buyers and sellers' objectives remain the same as described in Equations (3) and (4). In terms of their trade strategies, the sellers in the clearinghouse market need to make the same decisions as those described above in the bilateral negotiation mechanism. However, the buyers will have fewer decisions to make in the discriminatory double auction since the responsibilities of selecting and matching themselves with suitable trading partners now reside with the independent auctioneer. As a result, a buyer in the clearinghouse market only needs to decide (i) whether to participate, denoted by the binary variable b_{1i}, and (ii) the offer price, which is a function of the continuous real variable b_{2i}. The presence of the auctioneer eliminates the uncertainty faced by the buyers in deciding the number of sellers who will be more likely to accept their offers and the need to figure out a ranking order among the accepting sellers with whom to finalize trades. With less uncertainty in the market, it is expected that the clearinghouse model will outweigh the bilateral negotiation model in various efficiency measures. To confirm such an expectation, a formal efficiency test was constructed for the two market structures in achieving the environmental targets at least cost subject to the regulator-defined rules of the market.

3 Efficiency Test

In the previous section, the trade strategies of buyers and sellers in both bilateral negotiation and clearinghouse markets were described. With *m* point source and *n* nonpoint source polluters in the market, the vector of (4**m*+2**n*) decisions taken by all participants in the market in the bilateral trading market is expressed as:

Equation 5

$$X = \left(b_{1i}, b_{2i}, b_{3i}, b_{4i}, s_{1j}, s_{2j}\right)$$

Given that costs are uncertain and that matching of buyers and sellers in bilateral trading has a random component, the pattern of trades associated with any *X*, and the associated costs, are not deterministic. There is instead a distribution of possible outcomes for any set of decisions. A draw of the exogenous parameters that define all agents cost functions and the random assignment of offers for each participating point source defines a realized state of the world. A market in each state of the world is defined by (8) and the resulting patterns of trade.

With the presence of the auctioneer in the clearinghouse market, a buyer does not need to decide on the number of sellers to contact and how to finalize trades with the sellers who accept its offer. The vector of decisions taken by all participants in the clearinghouse market contains ($2*m+2*n$) elements and is expressed as:

Equation 6

$$Y = (b_{1i}, b_{2i}, s_{1j}, s_{2j})$$

Unlike the bilateral negotiation structure, there is a unique assignment of offers for each participating point source, hence, a unique pattern of trade determined by the auctioneer in the discriminatory double auction. However, the presence of the auctioneer does not eliminate the uncertainty in abatement costs. As a result, the cost outcome of the market is still stochastic while there is a unique pattern of trade associated with any decision vector *Y*.

The performance of any market resulting from a given decision vector is, therefore, governed by its component agents' trading strategies and its overall resulting allocation of pollution abatements. To create a strong test for the potential efficiency of bilateral trading and trading through a clearinghouse, the powerful Differential Evolution algorithm is used to discover strategies that maximize the probability of achieving efficient outcomes over a wide range of exogenous parameter sets within each market structure. Thus, we do not ask how strategies would evolve, but instead seek efficient strategies within the basic market rules and coordination mechanisms. The expansive algorithmic search utilized in the simulations seeks to maximize water quality trading market performance. In particular, trading strategies that minimize the expected cost of pollution abatement are sought:

Equation 7

$$E[TCC] = \sum_{i=1}^{m} E[BIFC_i + BCC_i + BAC_i^*] + \sum_{j=1}^{n} E[SIFC_j + SCC_j + SAC_j]$$

subject to the trading rules established by the water quality authority, the structure of transactions implied by either bilateral negotiations or the clearinghouse market structure, and the bounded rationality of the agents.

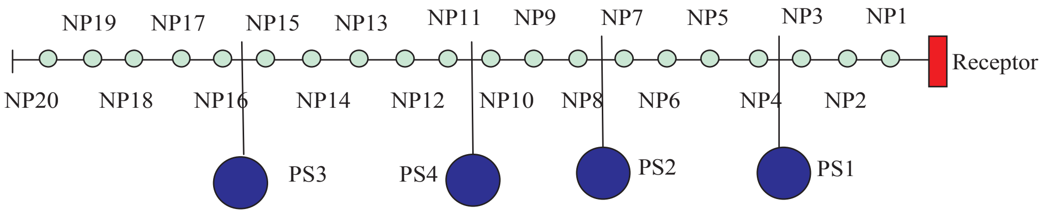
The expected total cost of pollution control in (7) provides a stochastic measure to evaluate the performance of the agent-based market models. For the bilateral negotiation mechanism, the outcome of the expected cost of pollution abatement is a function of the decisions taken by all the participants in the market, i.e. $\boldsymbol{E}[\boldsymbol{TCC}] = \boldsymbol{f}(\boldsymbol{X})$. Similarly, for the clearinghouse market, $\boldsymbol{E}[\boldsymbol{TCC}] = \boldsymbol{f}(\boldsymbol{Y})$. Solving (7) for each of the market models is a nontrivial optimization problem even for a small number of traders given the mix of binary, integer, and continuous decision variables, in combination with heterogeneous, non-convex and non-linear abatement cost functions. Minimizing the expected cost of pollution subject to the institutional, behavioral, and informational constraints imposed would require traders to select strategies that solve this complex problem without consciously or cooperatively seeking to do so. Given this complexity, a heuristic algorithm capable of providing good approximations for difficult problems was used, specifically, the Differential Evolution algorithm (Storn and Price 1997). The Differential Evolution operators represent meta-forces that drive market trade strategy X in a bilateral negotiation market or Y in a clearinghouse market to its best known solution that is robust under uncertainty and shown to minimize the expected value of the cost function given in equation (7). To clarify, a successful application of the algorithm yields a 'robust' market trade strategy, denoted X^* and Y^* (for bilateral negotiation and clearinghouse market, respectively), that performs well, compared with alternatives, across a wide range of plausible states of the world (Lempert 2002, Jin and Branke 2005). Given the uncertainties in evaluating the cost performance of trading strategies, the concept of robustness is important for reducing the influence of evaluation errors.

4 Market Simulation and Computational Experiments

Similar to the agent-based model of bilateral negotiations in Nguyen et al. (2010), we simulate the clearinghouse markets of $m = 4$ point source and $n = 20$ nonpoint source polluters. The point sources are large in terms of their emissions relative to the nonpoint sources. This design is representative of the fact that credit buyers in nutrient markets will typically be publicly owned waste treatment facilities that are small in number and large in size relative to the farms that will typically be credit sellers. Figure

1 presents a schematic of the simulated watershed that contains all of the point and nonpoint agents.

Figure 1: Schematic of the Simulated Watershed



Note: PSi, *i* = 1 to 4, are point source *i*, NPSj, *j* = 1 to 20, are nonpoint source *j*

To enable the comparison market performance between the two market structures, the same physical environment and the same agents (in terms of their characteristics) are used for both market simulations. The characterization of agents' abatement cost functions and various other cost components are the same as in Nguyen et al. (2010). The agents are simulated in such a fashion that there is a high degree of heterogeneity in control costs across polluters. A large number of possible draws of transactions and abatement cost parameters is used in the simulations to provide a large range of alternative states of the world and to carefully identify robust trading strategies.

4.1 Market Simulation

In the bilateral negotiation, for a market of 4 point sources and 20 nonpoint sources, the robust trade strategy, X^*, that minimizes equation (7) has 56 elements ($4*m+2*n = 4*4 + 2*20 = 56$). For the clearinghouse market, since the auctioneer assumes the responsibilities of selecting and matching trading partners, the robust market trade strategy, Y^*, that minimizes equation (7) in this market structure, has only 48 elements ($2*m+2*20 = 2*4 + 2*20 = 48$). These are nontrivial numbers for the complex mix of binary, real and integer decisions. Combining these decision vectors with heterogeneous, continuous and discontinuous abatement cost schedules, equation (7) is a highly non-linear, non-convex and discontinuous objective function.

The Differential Evolution algorithm is used to populate the decision space and search for the trade strategies that optimize (7). Nguyen et al. (2010) provide a detailed description of how the Differential Evolution algorithm works in simulating various possible combinations of decision strategies in the bilateral negotiation mechanism and seeking the robust least cost trade strategies. In summary, the Differential Evolution algorithm operates on an initial population of market trade strategies. The mutation and crossover operators in the Differential Evolution algorithm modify this initial population and the selection operator picks the population members in either the initial population or the newly created population that perform better in the bilateral negotiation loop. In the current paper, market trade strategies are tested under the discriminatory double auction. The expected cost of pollution control in (7) is calculated for trade strategies in the discriminatory double auction and serves as the criterion in the selection process. The new and 'evolved' generation contains market trade strategies that succeed in the selection round. The same process of mutation, crossover and selection is repeated for this new generation and for a maximum number of generations, specified by the modeler.

Essentially, the Differential Evolution algorithm was used in two separate simulations, one that uses bilateral trading as a means to test market trade strategies (Nguyen et al. 2010) and the other uses a clearinghouse (current study). For the purpose of comparing the two market structures, the same parameters in the algorithm in Nguyen et al. 2010 were used. A summary of the algorithm parameters is presented in Table 1. The rationale for choosing these values for the algorithm parameters is given in the previous study.

Table 1: Differential Evolution Algorithm Parameters

Parameter	**Notation**	**Value**
Population size	M	50
Number of trials (replicate simulations)	R	50
Monte Carlo Bilateral Negotiation or Discriminatory Double Auction	K	700
Number of generations (Evolution time)	G_{max}	560
Mutation constant	mc	0.6
Cross over probability	cr	0.9

In each generation of the evolutionary search, there is a trade strategy that is associated with the lowest expected total costs of pollution control for the whole watershed. Such a trade strategy is called a generational best known robust least-cost solution. In every trial r, there are 560 such solutions. From this set of generational best known robust least-cost solutions for a particular trial r, the trial best known robust least-cost solution is identified. For $R = 50$ trials or replicate simulations, there are 50 trial best known robust least-cost solutions. In a market design, there is a best-of-the-best solution in all trials, *X** in the bilateral negotiation or *Y** in the clearinghouse market.

4.2 Computational Experiments

Within each market structure, two key parameters in the design of water quality trading markets are the uncertainty trade ratio (designated as $t = 0.5$, 1.0 or 3.0) and the pollution load target (designated as low (LET), medium (MET) or high (HET) environmental target). These trade policy parameters are trading rules that determine the quantity of pollution rights that can be traded. The results explore the nine market design scenarios that capture the full set of combinations of these policy parameters, as presented in Table 2. The pollution load target refers to the sum of the limits imposed on individual point sources, $\sum_{i=1}^{m} \hat{a}_i$. The "High target" is 100 per cent higher than the "Low target" and 36 per cent higher than the "Moderate target". Uncertainty trade ratio experiments are conducted with value of t less than, equal to, and greater than unity. The specifications reflect contrasting views on how to set uncertainty trade ratios between the economic literature on trading design and the design of actual trading programs (Malik et al. 1993; Horan and Shortle 2005; Shortle and Horan 2008).

The experiments on transaction costs are limited to testing the effects of the presence of transaction costs, rather than testing the effects of individual transaction cost components. Transaction costs are the sum of information, exchange, and monitoring costs. Most *ex ante* assessments in existing literature on water quality trading have ignored transaction costs. *Ex post* assessments, however, indicate that transaction costs are ubiquitous and nontrivial (McCann and Easter 1999; McCann et al. 2005). The two treatments of transaction costs are, "Without Transaction Costs" and "With Transaction Costs". For two market structures, two transaction cost treatments and nine combinations of uncertainty trade ratio and pollution load target, a total of 36 scenarios were examined in this analysis.

Table 2: Alternative Specifications of Trade Ratio and Environmental Target

	Trade ratios		
Environmental targets	$t = 0.5$	$t = 1.0$	$t = 3.0$
Low Target	CASE 1	CASE 2	CASE 3
Moderate Target	CASE 4	CASE 5	CASE 6
High Target	CASE 7	CASE 8	CASE 9

The current analysis of the market for any specification of program design parameters within either of the market structure is limited to a set of R trial best known robust least-cost solutions, which is a subset from the complete set of solutions produced by the 50 independent evolutionary trials (R = 50 independent evolutionary trials, each of which contains M = 50 candidate trade strategies, evolved over G_{max} = 560 generations). Each robust solution emerges from an independently generated random population of 50 trade strategies that were evolved for 560 generations. The total number of solutions examined for each market design parameters scenario equals 50 market trade strategies times 560 generations times 50 trials per case (i.e., 1.4 million candidate solutions or market trade strategies are evaluated to attain top performing solutions). The expected total cost of pollution control for each scenario is averaged over 700 Monte Carlo draws and their mean cost is used to guide selection in the Differential Evolution search. For each market design parameter scenario 1.4 million market trade strategies are evaluated using 700 Monte Carlo draws yielding a total of 980 million cost calculations for any particular market design scenario (Table 2).

5. Results

The best-of-the-best solution in all trials of a particular scenario, X^* in the bilateral trading mechanism and Y^* in the clearinghouse market, is used to examine the market outcomes and the effects of the uncertainty trade ratio, pollution load target, and transaction costs on the market. Essentially, the analysis is seeking to determine how trade policy parameters and transactions costs affect outcomes when the market does comparatively well with respect to collective cost minimization under uncertainty. Statistical measures of market efficiency, polluter participation rate, trade volumes and the proportion abatement requirement achieved through trading for markets governed by X^* and Y^* have been computed using an independent large statistical sample (i.e. separate from the optimization) of the solutions' cost parameters (K = 2000) in the Monte Carlo bilateral negotiation and discriminatory double auction The independent sampling accurately captures the market's statistical performance and serves as a confirmation of the solutions' robustness.

5.1 Market Efficiency Comparison

To compare the efficiency of bilateral trading with trading in a clearinghouse market in achieving robust best known least-cost solutions, four market performance measures are used. These measures include market efficiency (MEF), participation rate (PR), trade volume (TV) and the proportion of abatement requirement achieved through trading ($POAR$).

Market efficiency (MEF) is measured by an index of the pollution control cost savings achieved through trading relative to the Autarky case (no trading):

Equation 8

$$MEF = \frac{E[TCC^{Autarky}] - E[TCC]}{E[TCC^{Autarky}]} * 100$$

If $0 \leq MEF \leq 100\%$, it can be said that costs with trading are lower than without.
If $MEF < 0$, trading results in increased costs.

The participation rate (PR) is the number of agents who register to trade in the market over the total number of agents in the watershed:

Equation 9

$$PR = \frac{NPA}{m + n} * 100$$

$0 \leq PR \leq 1$, where NPA = number of participating agents, and $m + n$ = number of agents in the watershed. Trade volume (TV) is the total number of credits exchanged in a particular treatment.

The proportion of abatement requirement ($POAR$) achieved through trading is defined in:

Equation 10

$$POAR = \frac{\sum_i \sum_j cr_{ij}}{\sum_i r_i}$$

$0 \leq POAR \leq 1$. The numerator of (Equation 10) is the total volume of trades and the denominator is the total abatement requirement.

The mean and standard deviation of MEF are presented in Table 3. There are several interesting results to note. First, MEF ranges from 35 per cent to 81 per cent in bilateral negotiations in the treatment without transaction costs. This range is 36 per cent to 92 per cent in the clearinghouse market. When transaction costs are taken into account, MEF in both bilateral negotiations and double auction are statistically lower than in the without transaction costs but still significantly positive. These figures suggest that with or without transaction costs, robust trade strategies produce significant cost-savings relative to the Autarky solution. Second, for every comparable pair of scenarios except for one (t = 3.0 and Med target with TC), the clearinghouse market is shown to be dominantly more efficient than bilateral negotiations in coordinating point-nonpoint trades. The mean market efficiency measure in each scenario of trade policy parameters under the clearinghouse market structure is higher than that under the bilateral negotiation mechanism. The standard deviation of *MEF* for any given scenario in the clearinghouse market is found to be lower than that in the same scenario under bilateral negotiations. The higher and less stochastic *MEF* under the clearinghouse market is not due to an increase in participation rates.

Table 3: Market Efficiency Outcome

		Bilateral Negotiations			**Clearinghouse Market**		
Without TC	*MEF*	$t = 0.5$	$t = 1.0$	$t = 3.0$	$t = 0.5$	$t = 1.0$	$t = 3.0$
	Low target	81 (4.82)	67 (4.04)	42 (3.58)	92 (0.693)	69 (2.11)	42 (3.64)
	Med target	79 (4.91)	60 (3.23)	35 (3.02)	91 (0.67)	60 (2.01)	36 (2.98)
	Hi target	78 (3.79)	61 (2.71)	38 (2.52)	82 (1.94)	62 (2.03)	38 (2.47)
With TC	*MEF*						
	Low target	67 (3.09)	61 (4.08)	41 (3.52)	76 (1.84)	63 (2.71)	41 (3.64)
	Med target	73 (6.28)	56 (3.57)	33 (2.91)	73 (1.94)	58 (2.56)	32 (2.83)
	Hi target	76 (4.12)	59 (2.91)	38 (2.29)	78 (1.99)	61 (1.97)	38 (2.35)
	*MEF**						
	Low target	50 (3.68)	43 (4.24)	29 (3.79)	59 (2.9)	48 (3.4)	31 (3.85)
	Med target	55 (5.68)	41 (3.68)	25 (2.97)	60 (2.69)	47 (2.92)	26 (2.9)
	Hi target	62 (3.89)	48 (2.93)	31 (2.33)	67 (2.12)	52 (2.14)	32 (2.37)

Note: *MEF* is the Market Efficiency index calculated without transaction costs in both "With" and "Without Transaction Costs" scenarios. *MEF** is the calculation of this metric including transaction costs in the "With Transaction Costs" scenario. TC denotes Transaction Costs.

As shown in Table 4, participation rates in the clearinghouse market are mostly lower than those in the bilateral negotiation mechanism. Although participation rate can be high in bilateral negotiations, coordination failures might lead to a very low number of successful trades**.** The higher efficiency outcome of the clearinghouse market is, in fact, due to the presence of the auctioneer. The auctioneer, as the central agent assuming the tasks of selecting and matching trading partners, helps to eliminate the uncertainty in agents' interactions, hence, reducing the stochastic nature of total cost of pollution control. The fact that the auctioneer is able to rank order buyers and sellers and match the highest bids with the lowest asks maximizes the gains from any particular successful trade. Uncertainty in agents' interactions is, however, an inherent consequence of bilateral trading when agents have asymmetric information about their trading partners' and their own cost structures.

Table 4: Participation Rates

PR		Bilateral Negotiations			Clearinghouse Market		
		$t = 0.5$	$t = 1.0$	$t = 3.0$	$t = 0.5$	$t = 1.0$	$t = 3.0$
Without TC	Low target	75	83	63	75	71	63
	Med target	83	75	71	88	79	75
	Hi target	79	83	71	79	83	75
With TC	Low target	42	50	33	42	33	33
	Med target	79	71	42	46	50	42
	Hi target	71	71	54	75	67	58

Note: TC denotes Transaction Costs.

The results on trade volumes and the proportion of abatement requirement achieved through trading also show that the clearinghouse market is more efficient than bilateral negotiations. In all treatment scenarios, with or without transaction costs, trade volume (*TV*) achieved through the discriminatory double auction is higher than that in bilateral negotiations, as shown in Table 5. As a result of higher trade volumes, the proportion of abatement achieved through trading in the clearinghouse market is also higher than that in bilateral negotiations (Table 6).

Table 5: Trade Volumes

TV		Bilateral Negotiations			Clearinghouse Market		
		$t = 0.5$	$t = 1.0$	$t = 3.0$	$t = 0.5$	$t = 1.0$	$t = 3.0$
Without TC	Low target	44 (5.64)	26 (3.42)	8.4 (0.354)	55*	31	8.3
	Med target	54 (6.09)	32 (2.72)	9.7 (0.307)	79	37	12
	Hi target	64 (5.3)	36 (2.95)	13 (0)	81	40	13
With TC							
	Low target	25 (3.17)	19 (3.13)	6.5 (0)	35	20	6.5
	Med target	46 (6.36)	27 (2.75)	7.6 (0)	53	28	7.5
	Hi target	60 (5.71)	34 (2.32)	12 (0)	70	37	12

Note: *the *TV* figures in the clearinghouse market are deterministic because there is a unique pattern of trade for each market trade strategy as opposed to multiple patterns of trade in bilateral trading. TC denotes Transaction Costs.

While the results validate the expectation that the clearinghouse market is more efficient than bilateral negotiations in coordinating point-nonpoint trading to achieve the pollution load target at lowest cost, it is important to keep in mind that the public costs of establishing the clearinghouse have not been explicitly modeled in the current research. The decision on whether to introduce a clearinghouse market or to allow bilateral trading among point and nonpoint polluters should, therefore, involve a comparison between the extra gains from trades in the double auction (beyond the gains in bilateral negotiations) and the costs of establishing a clearinghouse.

Furthermore, the analysis of market performance for both the bilateral negotiation mechanism and the clearinghouse market is conducted on the most successful solution (trade strategies) in each treatment. Therefore, positive gains from trade do not necessarily warrant the conclusion that bilateral trading or discriminatory double auctioning is always more beneficial than traditional command-and-control policies, even when public transaction costs are ignored.

Table 6: Proportion of Abatement Requirement Achieved Through Trading

POAR		**Bilateral Negotiations**			**Clearinghouse Market**		
		t = 0.5	*t* = 1.0	*t* = 3.0	*t* = 0.5	*t* = 1.0	*t* = 3.0
Without TC	Low target	73 (9.39)	43 (5.71)	14 (0.59)	92*	52	14
	Med target	61 (6.92)	36 (3.09)	11 (0.349)	89	42	14
	Hi target	54 (4.41)	30 (2.46)	11 (0)	68	33	10
With TC							
	Low target	42 (5.29)	32 (5.22)	11 (0)	58	33	11
	Med target	52 (7.23)	30 (3.12)	8.6 (0)	60	32	8.6
	Hi target	50 (4.76)	29 (1.93)	9.7 (0)	58	31	9.9

Note: * the *POAR* figures in the clearinghouse market are deterministic because there is a unique pattern of trade for each market trade strategy as opposed to multiple patterns of trade in bilateral trading. TC denotes Transaction Costs.

5.2 Effects of Transaction Costs and Trade Policy Parameters

Within each market structure, it is possible to examine the effects of the uncertainty trade ratio and the total pollution load target as well as transaction costs on the outcomes of the market. Several interesting findings are noted.

In both bilateral trading and trading in the discriminatory double auction, transaction costs lower market efficiency. This is expected since transaction costs would depress trading activity needed to realize cost savings (Stavins 1995). As shown in Table 3, in bilateral negotiations, without transaction costs, *MEF* ranges from 35 per cent to 81 per cent whereas the range reduces to 33 per cent to 67 per cent in the presence of transaction costs. A similar story is found in the clearinghouse market. *MEF* is within the range of 36 per cent to 92 per cent without transaction costs and from 32 per cent to 76 per cent with transaction costs.

The effects of transaction costs on participation and trade volume are apparent in Table 4 and Table 5. Overall, transaction costs reduce market participation and the volumes of trade. The percentage of agents participating in the markets without transaction costs ranges from 63 per cent to 83 per cent in bilateral negotiations and 63 per cent to 88 per cent in the double auction. This range decreases to [33%, 79%] and [33%, 75%] for bilateral trading and the clearinghouse market, respectively, in the simulations with transaction costs. Trade volume in markets without transaction costs ranges from an average of 8.4 to 64 credits in the bilateral negotiation mechanism and 8.3 to 81 credits exchanged in the double auction. The range decreases to about 7.6 to 60 credits on average in the bilateral negotiation simulations with transaction costs and 6.5 to 71 credits in the clearinghouse market. The reduction in participation due to the presence of transaction costs limits the opportunities for buyers to find trading partners, either bilaterally or matched centrally. At the same time, transaction costs put an upward pressure on sellers' reservation prices and a downward pressure on buyers' bid prices. Credits become more expensive to obtain in the presence of transaction costs, which deters point sources seeking credits from nonpoint sources in the bilateral negotiation case. For the clearinghouse market, lower bid prices and higher ask prices also reduce the number of matches that could have occurred without the increase in marginal costs due to transaction costs. As a result, fewer trades can be matched, leading to a lower number of successful trades. The reduction in the total trade volume reflects the decline in successful matches and in the number of credits exchanged.

Without transaction costs, bilateral trading achieves between 11 per cent and 73 per cent of total abatement requirement while trading in the clearinghouse market between 10 per cent and 92 per cent. The range with transaction costs is 9.7 per cent to 52 per cent for bilateral trading and 8.6 per cent to 60 per cent for the clearinghouse market. The results show that the proportion of abatement requirement achieved through trading decreases with transaction cost regardless of the market structure used.

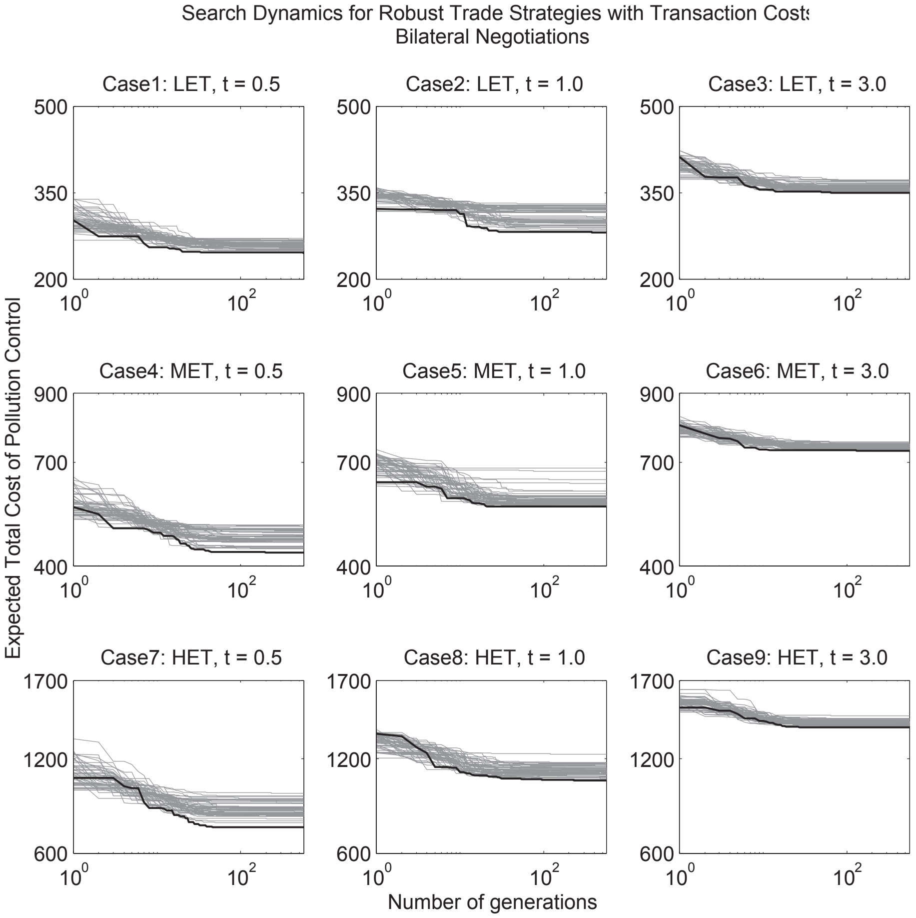
The effects of uncertainty trade ratios on the performance of the market under both bilateral trading and trading in the clearinghouse market are as expected. Larger uncertainty trade ratios reduce *MEF*, *PR*, *TV* and *POAR* in all cases. An uncertainty trade ratio greater (less) than one is equivalent in its incentive effects to a tax (subsidy) on the purchase of credits. The increased (decreased) cost of purchasing credits, depresses (increases) market participation (*PR*), trade volume (*TV*), and therefore market efficiency (*MEF*). The effects of tightening the environmental target on various *MEF*, *PR* and *POAR* in most cases within each market structure demonstrate a non-linear trend. Trade volume, however, is seen to be consistently increasing when the pollution load target is made more restrictive. A more restrictive environmental target translates into higher demand for pollution abatement for all point source polluters, which subsequently creates more opportunities for trades within any particular market structure if the point sources perceive trading as a method that lowers the total cost of pollution control rather than implementing own abatement effort. As a result, more successful trades are probable and a bigger number of credits can be exchanged.

5.3 Probability of Attaining the Best-of-the-best Solution

It is of particular interest to compare the likelihood of the market attaining the best-of-the-best solution under the two market structures. Such a comparison can enable policy makers to adopt a more efficient market structure that can potentially achieve the least-cost allocation. Figure 2 and Figure 3 trace the evolution of the generational minimum expected total pollution control costs (computed across 700 Monte Carlo draws) for the 50 replicate simulations in each of the market design and market structure treatments. Only the figures for the scenarios with transaction costs are presented here. The search evolution figures for the same scenarios in the absence of transaction costs are included in the Appendix.

Referring to Figure 2 and Figure 3, the bold trace in black represents the expected total cost evolution of the best-of-the-best solution X^* and Y^* in each policy treatment, for bilateral negotiations and the clearinghouse market, respectively. The traces depict how the sample averages of total control costs change as the evolutionary algorithm searches for market trade strategies that minimize the expected total cost of pollution control. The traces would steadily and rapidly decrease to the best-of-the-best solution if the associated trade strategies were easily discovered from any initial draw. Further, while the initial costs would show a degree of variation consistent with initial draws, the traces would quickly converge to the best-known minimum if the associated trade strategies were easily discovered. Instead, there is a cost band in both the bilateral and clearinghouse market structures, the width of which indicates the difficulty and divergence of the expected total cost of pollution control in each treatment of market design and structures. It is notable that even with lower bound complexity in agents' behaviors and interactions and the aid of the powerful Differential Evolution algorithm, the existence of a cost band for any particular market design and structure shows that it is difficult for the market to gravitate toward its best known robust least-cost solution. The implication of such finding is that real world water quality trading markets with much higher complexity are not likely to arrive at the least cost solution intended by the social planner.

Figure 2: Process of Attaining the Robust Best-of-the-Best Solution in Bilateral Trading with Transaction Costs



Note: t = trade ratio, LET = Low Environmental Target, MET = Medium Environmental Target, HET = High Environmental Target

_____: Search traces of the best known robust least-cost solutions in *R* trials

_____: Search trace that contains the best-of-the-best solution in all trials and all generations

To provide a sense of the success or failure of markets to attain robust, low cost solutions, the frequency with which each least-cost trade strategy in the 50 replicate simulations converges to the best-of-the-best solution (minimum of all the 50 least-cost solutions)[4] was considered. In Table 7, it can be seen that in the majority of treatments, the clearinghouse market has a higher probability of achieving the best-of-the-best solution than bilateral negotiations. Without transaction costs, given a low uncertainty trade ratio and high environmental target, bilateral trading fails to achieve the best-of-the-best solution 98 per cent of the time, while the failure rate for a clearinghouse is only 92 per cent. When transaction costs are present, the lowest failure rate for the clearinghouse market is 40 per cent whereas that for bilateral trading is 16 per cent.

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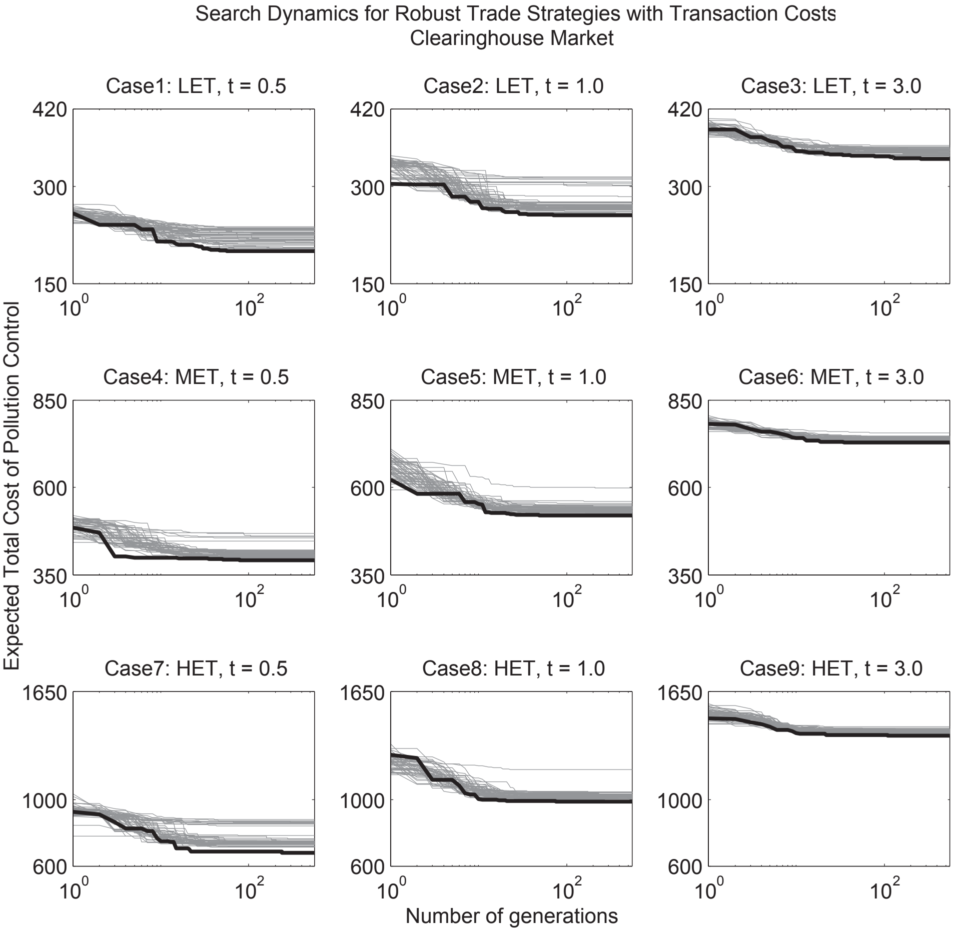
[4] A market is considered to successfully converge to its best known equilibrium if the mean cost associated with this market is within 10 per cent of the best known robust least cost solution's mean cost.

Figure 3: Process of Attaining the Robust Best-of-the-Best Solution in Clearinghouse with Transaction Costs



Note: t = trade ratio, LET = Low Environmental Target, MET = Medium Environmental Target, HET = High Environmental Target

—: Search traces of the best known robust least-cost solutions in *R* trials

—: Search trace that contains the best-of-the-best solution in all trials and all generations

Table 7: Probability of Success in Attaining Robust Solution

		Bilateral Negotiations			Clearinghouse Market		
		t = 0.5	*t* = 1.0	*t* = 3.0	*t* = 0.5	*t* = 1.0	*t* = 3.0
Without TC	Low target	12	42	100	20	58	100
	Med target	10	62	100	6	100	100
	Hi target	2	64	100	8	98	100
With TC	Low target	98	52	100	40	82	100
	Med target	48	92	100	90	98	100
	Hi target	16	92	100	62	98	100

Note: A solution is considered to successfully converge to the best-of-the-best solution in all trials if its expected cost is within 10 per cent of the best-of-the-best solution's expected total cost. TC = Transaction Costs

Higher uncertainty trade ratios have the same impacts on the probability of achieving the best-of-the-best solution as the inclusion of transaction costs. As uncertainty trade ratios increase from 0.5 to 3.0, lower level of participation and less trading activity result (see Tables 4-6). However, the improvement in success rate of attaining the best-of-the-best solution implies that the market seems to fail in attaining its “best known” least-cost solution in cases where there is more trading activity. The intuition behind this can be obtained when investigating the nature of these cases. The cases with less trading activity are strongly influenced by transaction costs. Transaction costs increase trading costs and discourage trading activities. As a result, the total costs of pollution control in these cases are dominated by point source own abatement efforts and not of expenses incurred in trading under uncertainties. The stochasticity of total control cost in each of these cases is greatly reduced. In consequence, the optimization is simpler and it is easier to discover the market trade strategies that are associated with low total control costs. It should be emphasized that markets with higher search success rates in achieving the best-of-the-best solution under both bilateral trading and the clearinghouse market should not be interpreted as being more efficient markets. Indeed, when referring to Table 3, the markets with 100 per cent success rate are the ones with the lowest market efficiency. The analysis here focuses solely on the market’s ability to achieve a best-of-the-best solution for the conditions, rather than the realized gains from trade. The key conclusion to draw from the probability of success is that for some specifications of market design parameters, markets can frequently fail to achieve the best-of-the-best solution. The magnitude of search failures depends strongly on the nature of agents’ interactions and is tied to transaction costs.

6 Conclusions

This research extends Nguyen et al. (2010) by assessing the performance of point-nonpoint credit trading within a clearinghouse market structure under asymmetric information and transaction costs. The assessment allows a comparison of the two market structures in coordinating trades between point and nonpoint sources to achieve the environmental target cost effectively. Moreover, the stochastic agent-based framework employed allows an explicit characterization of agents’ heterogeneity in abatement costs and decision making with asymmetric and imperfect information, as well as transaction costs.

The simulation results confirm the expectation that the clearinghouse market is more efficient than the bilateral negotiation mechanism in coordinating point-nonpoint trading under uncertainty and transaction costs. However, the decision on whether to introduce a clearinghouse market or to allow bilateral trading should involve a comparison between the extra gains from trades in the double auction (beyond the gains in bilateral negotiations) and the costs of establishing a clearinghouse. While market efficiency is higher in the clearinghouse market, this result does not stem from the fact that higher participation is observed in the clearinghouse. The higher efficiency in the clearinghouse structure is due to the role of the auctioneer in reducing uncertainty in trading partners' selection and matching.

The results also show that trading in both market structures yields net cost savings relative to the Autarky solution in each treatment case only when the maximum computational capacity is given to each agent and agents' behaviors and interactions are modeled with lower bound complexity. The analysis of market performance is conducted on the most successful solution in each treatment. Therefore, the positive gains from trade do not necessarily warrant the conclusion that bilateral trading or trading in a clearinghouse is always more beneficial than traditional command-and-control policies, even when public transaction costs are ignored. Both transaction costs and trade policy parameters are found to have discernible impacts on market outcomes.

High rates of failure of the market in converging to its best-of-the-best solution are observed in both bilateral negotiation and clearinghouse markets. The result shows that a market outcome induced by complex interactions among agents under many sources of uncertainty might not be the least cost solution to the planner's deterministic optimization problem. The clearinghouse market structure has a relatively lower frequency of failure than the bilateral trading mechanism, suggesting that if markets are to be used to reallocate point-nonpoint pollution reductions, the clearinghouse is more efficient in coordinating trades among agents. The high failure rates also imply that the least cost solution is not a good prediction of the market. As a result, market designs based on the assumption that the market can achieve the least cost solution, ignoring the presence of complexities in decision making and interactions are not meaningful in practice.

Appendix

Figure 4: Process of Attaining the Robust Best-of-the-Best Solution in Bilateral Trading without Transaction Costs

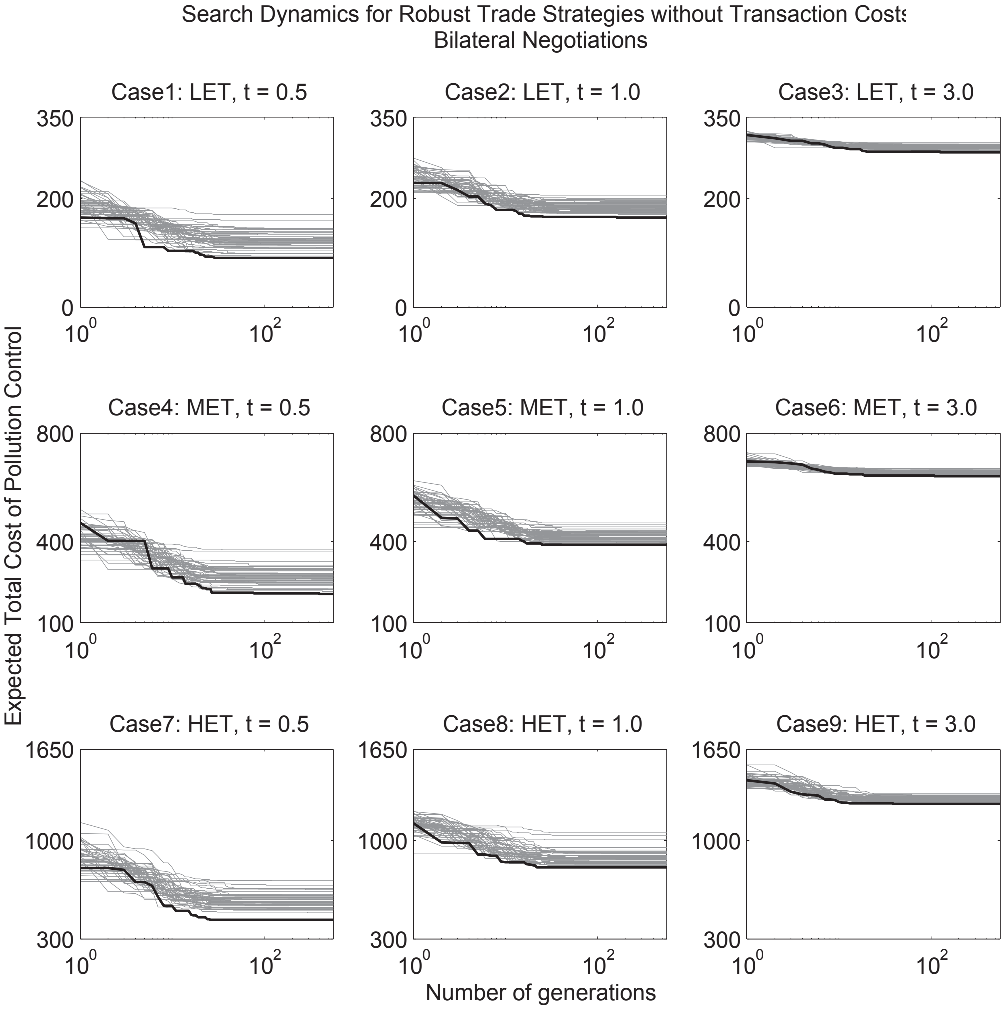
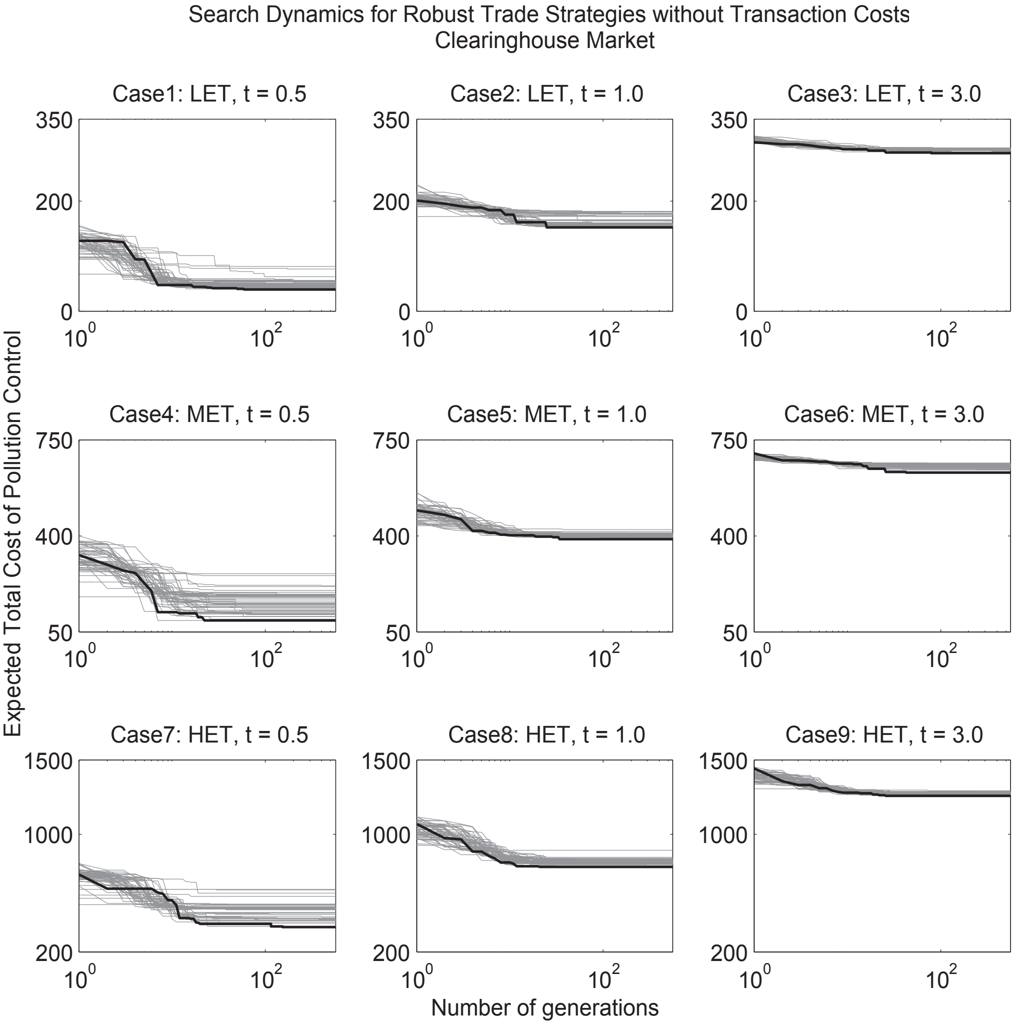


Figure 5: Process of Attaining the Robust Best-of-the-Best Solution in Clearinghouse with Transaction Costs



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