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Integrating watershed hydrology and economics to establish a local market for water quality improvement: A field experiment

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Abstract

Innovative market mechanisms are being increasingly recognized as effective decision-making institutions to incorporate the value of ecosystem services into the economy. We present a field experiment that integrates an economic auction and a biophysical water flux model to develop a local market process consisting of both the supply and demand sides. On the supply side, we operate an auction with small-scale livestock owners who bid for contracts to implement site-specific manure management practices that reduce phosphorus loadings to a major reservoir. On the demand side, we implement a real money, multi-unit public good auction for these contracts with residents who potentially benefit from reduced water quality risks. The experiments allow us to construct supply and demand curves to find an equilibrium price for water quality improvement. The field experiments provide a proof-of-concept for practical implementation of a local market for environmental improvements, even for the challenging context of nonpoint pollution.

Keywords

hydrologic ecosystem services; water quality; market-based approach; auctions

INTRODUCTION

Ecosystems provide many services that society values, but some ecosystem services are threatened by development and pollution (De Groot et al. 2002). Water quality is one such ecosystem service that provides benefits including drinking water, recreation, aesthetics, and nonuse values, but is at risk from pollution (Brauman et al. 2007). Pollution stemming from agricultural practices can introduce excess nutrients into freshwater bodies, causing harmful algal blooms and deteriorated water quality (Correll 1998, Carpenter et al. 1998). This

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nonpoint source pollution is difficult to address because of the large number of actors involved, the complex feedback relationships between land management decisions and hydrology, those who are affected by pollution often differing from those who cause the problem, and the fact that water quality is a public good. The benefits of a public good cannot be made exclusive to those who pay for them, resulting in free-riders who benefit from the public good without paying for it. Therefore, we expect public goods like water quality to be systematically undervalued and underprovided when their existence depends on private donations. Our research addresses this challenge by introducing and testing an economic market that connects demand for improved water quality with farmers to fund manure management practices.

Market mechanisms (e.g. auctions) are increasingly recognized as effective ways to incorporate the value of ecosystem services into the economy (Banerjee et al. 2013). Markets work by providing incentives for generating or preserving ecosystem services and aligning public and private interests. In fact, conservation auctions have been implemented at various scales in the United States (e.g., Thurston et al. 2010, Hellerstein et al. 2015), Canada (Hill et al. 2011), Australia (Eigenraam et al. 2006), Europe, and elsewhere. However, the vast majority of these markets have been one-sided, only considering either demand for conservation or supply of ecosystem services (e.g., Swallow et al. 2008, Jack et al. 2009, Thurston et al. 2010, Boxall et al. 2013).

To address this gap, we present a field experiment to demonstrate a market approach for water quality improvements. We integrated a supply-side auction for improving water quality with a demand-side auction to fund local water quality improvements. Our setting involved livestock owners within a reservoir watershed as “sellers” in the supply-side auction and local residents of that watershed as “buyers” in the demand-side auction. The market addressed nonpoint source pollution caused by phosphorus contained in animal manure. In the supply-side auction, we solicited bids from livestock owners to install gutters that redirect rainwater from manure piles and to install better manure storage, thereby improving phosphorous levels in the watershed. In the demand-side auction, we solicited bids from local residents to pay for marginal improvements in phosphorus levels. Together, these auctions allowed us to determine an equilibrium price and quantity of phosphorus reductions. We found a positive willingness to contribute for reducing cow manure by farmers improving their manure management. Residents’ payments coupled with an external funding funded three actual manure management projects, demonstrating the viability of this market approach.

The first primary contribution of this research is integrating the supply-side auction and demand-side auction within the market. In contrast to a one-sided auction, having an auction process on both the demand and supply sides of the market can lead to a more efficient market. Our approach allows the organization running the market (the market maker) to compare the supply cost to demand for ecosystem services at the margin, allowing the market maker to endogenously determine the quantity of services provided and price received by suppliers. In designing such a market, the auction mechanisms used should generate the price signals from the participants in a manner reflecting their true value or cost of the good or service provided in order to realize market efficiencies (Griffiths et al. 2012,

Boyd and Krupnick 2013). Therefore, we also tested the effectiveness of a recently developed type of auction aimed to reduce incentives for free-riders, who benefit from a public good without paying their full value for it, an Individual Price Auction (IPA) (Smith and Swallow 2013, Swallow 2013). We coupled this demand side with a procurement auction designed to identify the least-cost providers of water quality improvements.”

The second contribution of this study is testing the viability of a market approach to improve a highly localized public good, of which water quality is a prime example. In contrast to other ecosystem services such as carbon sequestration, improvement in water quality primarily affects only local residents whose values may vary widely (Keeler et al. 2012). We address the need to understand the ecological process that links actions (e.g. of livestock owners) to the provision of ecosystem services valued by individuals at the relevant spatial scale (Keeler et al. 2012, Boyd and Krupnick 2013). Previous studies on markets for water quality are often not quantitatively linked to changes in management, land use and other actions that lead to water quality improvement (Bateman et al. 2011). To do so, we use a spatially explicit hydro-ecological model of watershed flux (SWAT). Using this model, we estimate the effects of specific manure management practices at particular farm sites on the level of nutrients within the reservoir system. This model allows the market to prioritize funding for farms that can achieve the largest reductions in pollution at the lowest costs. Doing so enhances allocative efficiency by providing the specific level of water quality preferred by and paid for by resident contributions. Additionally, our approach is unlike other market-based approaches to water quality under, for example, a cap and trade institution that relies upon government regulatory power to obviate the need for a beneficiary-driven demand sector (Shortle 2013). Although the size of this pilot experiment is too small to restore the water quality of the watershed and hence serves as a proof-of-concept, the intent of the experiment is to evaluate the market approach, and to inform design in scaling up the effort if the approach is found viable. Our approach demonstrates a way to integrate a hydrological model with an economic market that establishes a protocol that the public accepts for linking action to impact, thereby enabling public consumers to focus on changes in the impact and its value to themselves.

DESIGN OF FIELD EXPERIMENT AND IMPLEMENTATION

Study Area

We conducted the field experiment in the Scituate Reservoir Watershed in Rhode Island. The watershed is 242 km², composed of a number of interlinked basins with a total surface area of 18.6 km². The reservoir system supplies water to more than 600,000 residents including the capital city of Providence, over 60 percent of the state’s population (Bellet et al. 2003a). The Providence Water Supply Board (PWSB) conserves and manages 25 percent of the watershed with the goal of maintaining, and ultimately improving, water quality of the reservoir system (Nimiroski and Waldron 2002, Bellet et al. 2003).

While the system as a whole maintains good water quality, studies have found one of the reservoirs in a mesotrophic state, with heightened levels of nutrients in the water (U.S. EPA 2014). Studies also found evidence of excessive nutrients in the water, or eutrophication, driven by high levels of phosphorus (U.S. EPA 2014). Nutrient-rich waters provide good

conditions for algae to grow. One particularly harmful type of algae is cyanobacteria, a species of blue-green algae capable of producing neurotoxins and hepatotoxins. Cyanobacteria have been reported in the study reservoir (ESS Group 2011). Blue-green algal blooms increase the concentration of organic matter in the water. When this organic matter is combined with chlorination used in the drinking water treatment process, it can foster trihalomethanes, chemical compounds known to increase risk of cancer in some people (U.S. EPA 2014). The presence of conditions capable of supporting cyanobacteria blooms makes prevention of further degradation in this sole-source drinking water reservoir a pressing health concern.

Excess phosphorus in the reservoir system is predominantly from rural, nonpoint sources, including small farm operations (< 3.5 ha) which constitute 35% of all farms in Rhode Island (USDA NASS 2014). Many of these farms raise livestock and contain areas of heavy livestock use with animal waste. However, these heavy-use areas often lack the necessary infrastructure or livestock owners lack the best management practices to prevent nutrients from the animal waste from entering the reservoir. Small-scale livestock operations in particular have substantial risk of off-site contamination due to a combination of high manure loads and low soil infiltration rates (McCullough et al. 2001). Off-site contamination could be curtailed with the use of well-tested management practices adopted by larger operations (USDA ARS 2006). However, small farm operations typically lag larger ones in adopting such practices, in part because they are not required by existing regulations (Fuglie and Kascak 2001).

While ongoing conservation and outreach efforts to reduce nonpoint source pollution like phosphorus from livestock farms are essential to improving water quality, market mechanisms could serve as a key additional watershed management tool. Designed to address these traditionally difficult-to-influence nutrient sources, markets could fill the gap of watershed management tools to maintain and ultimately improve the conditions in this reservoir and others with similar diffuse nutrient sources.

Supply-Side Auction

The objective of the supply side is to replicate the marginal cost curve for phosphorous reductions. To do so, we conducted an auction with small-scale livestock farmers operating within the reservoir watershed who were recruited through collaboration with local conservation organizations, focus groups, mailings, and a door-to-door recruitment campaign. Seven farmers with operations ranging from 2 to 250 livestock participated in the auction. An expert and extension staff person visited each farm to understand the scale of operation and current manure management practices, conduct soil tests for nutrients and a wetlands evaluation, and evaluate safety and legal restrictions for participation in the study. They then recommended one or both of two projects to improve manure management: i) construct a concrete containment pad to store manure, and ii) install gutters to redirect rainwater from areas with manure. We selected these two projects because they are appropriate for small-scale livestock farms and require minimal maintenance, reducing the need for costly monitoring and complex contracts.

Farmers participated in a type of auction called a uniform-price reverse auction (UPRA; Ferraro 2008). We asked farmers to submit the lowest price they would be willing to accept to implement the project. All bids were binding, meaning that if the market funded the bid, the farmer must implement the project at the price she/he set by the auction (at or above the farmer's submitted-bid). The seven participating farmers submitted 13 bids in total, with six farmers submitting a bid for each of the two projects (see Appendix S2 for auction text). We then estimated the equivalent cost to reduce a unit of phosphorus for each farm's manure management project, resulting in bids that were in terms of *\$ per kilogram of phosphorus reduced per year* (\$ per P kg y⁻¹; we detail these methods in the next section).

In the market experiment, we accepted bids based on the available revenue from consumers, setting a uniform price per kilogram P paid to all farmers contracted for supply. The market maker orders all bids from lowest cost per unit of P reduction at the reservoir to the highest and identifies a transaction price equal to the highest uniform price for emissions that does not violate the budget constraint. All bids below that transaction price are purchased, while all higher bids are rejected. In a UPRA, the "first rejected bid" is the lowest bid that exceeds the transaction price.

To understand why this type of auction elicits bids close to the farmer's true minimum cost that they would be willing to accept, one needs to understand the incentives for the farmer creating a bid.^X Because farmers would always be paid an amount larger than their bids if their bid is accepted, they have an incentive to reveal a price close to their actual opportunity cost to install a manure management project, knowing the auction will cover that cost and possibly provide a profit. The price of the bid affects whether or not the bid is accepted, but does not affect the transaction price that is received if the bid is accepted. As a farmer's bid becomes greater than their cost, there is an increasing chance that their bid could be rejected. As a result, profit for the farmer would be higher if their bid were lowered below the transaction price. As a consequence, the farmers would be expected to maximize expected profit by submitting bids that are close to their cost of emission reduction.¹

In other words, an UPRA is incentive compatible, as farmers compete to offer lower bids and doing so never reduces their payment relative to the price the available revenue will generate. One might argue that because farmers with accepted bids are paid more than their minimum willingness to accept, the costs of implementing these projects is higher than necessary. Ferraro (2008) reviews these considerations, while others estimate how much alternative auctions depart from a least-cost process (Latacz-Lohmann and Van der Hamsvoort 1997, Kirwan et al. 2005). Because the UPRA is incentive compatible, any additional revenue that farmers make from the auction represents a transfer from residents to farmers that maintains social welfare without loss of economic efficiency.

¹These principles hold when each seller offers one unit. Our supply-side experiment allows each farmer to submit at most two bids but only one for each type of manure management practice, and hence farmers' incentives are similar to a single-unit auction. For experimental analyses of multi-unit auctions in general, see, for example, List and Lucking-Reiley (2000) and Kagel and Levin (2001). One disadvantage of a single-unit auction is that it can lead to a lumpy supply curve (Tenorio 1993; Hailu and Thoyer 2006), which is the case with our supply-side auction. A full multi-unit auction would allow bidders to sell multiple units through a bidding process and the submitted bids would represent supply schedules, thereby help avoid this 'lumpy bid' problem (Tenorio 1993).

After receiving bids to implement manure management projects, we estimated the impact of these projects on reducing phosphorus in the reservoir system using the Soil and Water Assessment Tool (SWAT; Arnold et al. 2012). SWAT is a hydro-ecological modeling tool that simulates the flow of contaminants in surface and groundwater, and is widely applied to evaluate the impacts of agricultural practices on water quality (Weber et al. 2001, Gassman et al. 2007, Michalak et al. 2013).² SWAT discretizes the watershed into unique combinations of soil, slope, land use, and sub-basin called Hydrologic Response Units (HRUs). We estimate potential changes in phosphorus levels from each farm's manure management project, as represented by its HRU. We explicitly integrated site-specific information about each farm's animal densities and types, soil phosphorus concentrations from on-site soil samples, location-specific weather, and other soil and elevation data. Using SWAT, we estimated each farm's site-specific contribution to phosphorus entering reservoir waters (phosphorus loading) and resultant reductions from manure management projects in terms of kilograms of phosphorus per year (P kg y^{-1}) (modeling details can be found in Appendix S-1).

We used the resulting SWAT estimates of reduced P-loadings from the farm bids to implement the UPRA based on the cost-effectiveness of each farm's (potential) actions on reservoir loadings. That is, we ranked the farmer's bids from the most to least cost-effective, thereby creating a supply curve. A bid is considered more cost-effective if the project removes a larger amount of phosphorous at the reservoir per dollar cost. Based on the UPRA, the ranked bids are to be accepted from the most cost effective up to the price exhausting the available budget established by revenue from the demand side. All winning bidders are paid the same dollar-price per unit of reduction in P-loadings at the reservoir, as described above for the UPRA.

Demand Side Experiment and Market Clearing Price

The objective of the demand side experiment is to replicate the demand curve. To do so, we recruited 99 residents of the reservoir watershed to participate in the demand-side auction. Our recruiting effort used flyers posted to the town email listserv, town websites, local newsletters, and on-the-ground distribution, as well as posters in public places. While the study reservoir does not provide drinking water to households living in the watershed, focus groups revealed that the watershed has use and non-use benefits for local residents. These amenities include recreation opportunities and providing a sense of environmental stewardship, among others. Additionally, focus groups revealed that local residents who work in or visit Providence may also benefit from the drinking water provided there.

Participants attended one of three two-hour workshops, led by the same moderator (see Text S3). Each session began with a scripted presentation that was designed to give a common review and understanding of the linkages between reduction in manure from the improved management practices, the ecological process of how reduction in manure results in reduction in phosphorous, and the resultant improvements in water quality. Focus groups

²More technically, SWAT is a process-based, spatially-explicit watershed modeling tool that simulates the flux of surface and groundwater-borne contaminants, with the ability to estimate the effects of land use change, land management practices, and climate change on watershed flux (Gassman et al. 2007).

revealed that a reduction in phosphorus was a difficult and abstract concept to understand. We instead explained the reduction in phosphorus in terms of the equivalent tonnage of manure that would yield that amount of phosphorus if deposited directly into the reservoir.³ We scaled tons of manure to kilograms of phosphorus using the ratio of 5 kilograms phosphorous per ton of manure (Chastain and Camberato 2003). For example, participants saw language similar to “This project would reduce phosphorus in 15 tons of cow manure per year from entering the reservoir.” Participants received \$50 compensation for their time and were provided an additional \$100 as their budget for the auction. Participants retained funds not used in the auction.⁴

Participants (buyers) participated in one of two auction types, as described below, with the auctions run in workshops on different nights. Participants available for the nights planned for both auction-types were randomly assigned to a night; otherwise, participants were accepted based on their availability, but were not informed prior to arrival of the auction type to be conducted during their workshop. We test the difference in contributions between these two methods for soliciting payment for manure management projects. There are many options in soliciting contributions, ranging from general, non-specific solicitations for a cause to those that define a level of good or service to be provided and a provision point that must be reached. From the donation solicitation literature, those mechanisms that define a good more specifically and with a provision point (i.e., minimum total contribution that needs to be met for the good to be provided) generate larger revenue than more general solicitations (Bagnoli and McKee 1991, Rondeau et al. 1999, 2005). Therefore, we test two mechanisms that are designed to elicit as much of the participants’ true value for the water quality improvements as possible.

Using two workshops, we solicited offers under an individualized price auction (IPA) (Smith and Swallow 2013, Swallow 2013). The IPA, as described next, has more desirable properties and incentives compared to a standard donation solicitation as the IPA attempts to elicit participants’ true marginal value of water quality improvements by reducing incentives to free ride or cheap ride.⁵ IPA does so by having a ‘provision point’, a minimum level required to deliver a unit, which eliminates the possibility of non-provision as an outcome when marginal benefit exceeds unit cost. Second, the IPA solicits the individual’s

³We acknowledge that manure is an ecological input rather than the final ecosystem service (water quality.) In the experiment, we explained to the subjects the direct linkage between cow manure and water quality. We explained to the subjects that cow manure contains phosphorous, and that excess phosphorous is bad for water quality. However, we did not provide the information on specific water quality changes in each experiment task.

⁴We recognize the literature on the *house money effect* (or *found money effect*), a term coined by Thaler and Johnson (1990) based on “mental accounting” theory proposed by Thaler (1980), to describe behavioral discrepancies due to an initial endowment given to participants to make decisions in economic experiments. They found that participants in risky lottery experiments, who have experienced monetary gains or profit, are often willing to take more risk because they do not treat those gains as their own money. There is mixed evidence on the presence of the house money effect in a variety of experimental settings suggesting that the effect may be specific to the environment being tested. While this effect has been found in dictator game experiments (Cherry et al., 2002; Engel, 2011), public good experiments (Harrison, 2007), experimental auctions (Ackert et al., 2006) and capital expenditures (Keasy and Moon, 1996), Clark (2002) and Cherry et al. (2005) did not find such effects in their public goods experiments. Spraggon and Oxoby (2009) reported a negative effect of the “windfall gain” on contribution in their public goods experiment.

In our field experiment, the research moderator repeatedly emphasized and encouraged participants to consider money given to them as their “out of pocket” money by highlighting the personal priorities they can spend money on if they decided to take the money home in both PowerPoint presentation and the instructions in the survey booklet; participants were encouraged to write down the goods, causes, or charity to which they would consider donating. Such reminders are expected to mitigate house money effects in our experimental settings.

⁵Still, IPA is not ‘incentive compatible’, i.e., participants may still gain by making offers that depart from their true willingness to pay.

willingness to donate in relation to the marginal unit(s) being provided, enabling individuals to name a lower per-unit donation as more units are provided, thereby creating an opportunity for buyers to generate additional surplus as the number of units provided increases (see Swallow (2013) for a more extensive description).

Liu and Swallow (2014) provide evidence from a laboratory experiment that the IPA generates higher contributions than a request to name and donate a fixed amount to each unit or task. The IPA approach elicits marginal, per unit offers from individuals asked to consider the quantity of P reduction available within a pre-defined task (defined below in Table 1); the IPA determines the outcome of an auction as the quantity of a public good where the sum of marginal per-unit offers from individuals equals or exceeds the marginal cost of delivering a unit. Participants were directed to consider a “price per ton manure” that they would offer to pay under each task if delivered, and were given a table that presented the total potential contribution their marginal price-per-ton offers implied (Figure S1). These offers on each task are summed across all people and this sum represents a point on an aggregate average revenue curve available for each unit, from this auction approach. We explained to buyers that the number of tasks delivered would be one task before the first task for which the combined contributions of participants in the workshops failed to cover the costs of delivery.⁶

We used manure management projects ranked from the most to the least cost effective based on the farmers’ bids offering a project in the supply-side auction. Farmers/landowners defined the projects in their bids. We define a “task” as a manure management project or a combination of projects for which a contribution is solicited from buyer participants. For example, the first “task” asks participants to offer payments to be made under the condition that contributions cover the costs of the first two most cost effective manure management projects, with a cumulative phosphorus reduction of about 32 Kg per year (Table 1). Projects were ordered by cost-effectiveness, and several projects were combined into one task to make subsequent “tasks” (Table 1). Participants were instructed to bid on each “task”, which included one or more project(s) in addition to the project(s) in the preceding task. They were instructed to consider the same total budget (\$100) for each task while making the contribution as described below. This means that each task represents the accumulation of P-reductions from all previous tasks.

In one other workshop, we simply asked for a lump sum donation for different levels of manure management. It was similar to the IPA auction, but elicits offers on projects within larger quantity-ranges and therefore simplifies the logistics of soliciting donations. We merged the 6 tasks pairwise into 3 sequential donation tasks. The solicitation asked participants to offer a lump sum payment to be made under the condition that contributions cover the costs of water quality improving projects within the range associated with each task. We explained that the benefits would only be delivered if the costs were covered by the sum of the participants’ donations. Additionally, any revenue from a donation task that failed to generate sufficient revenue to implement that task would be returned to the donor in

⁶Potential total contributions were not allowed to exceed \$100. On successive tasks, individuals in the IPA Workshops were directed that their offered price-per-ton should not exceed the price-per-ton offered on the preceding task.

proportion to what was donated in this auction. Thus, this structured donation auction mechanism is a multi-unit version of the provision-point mechanism studied by experimental economists (e.g., Marks and Croson 1998, Spencer et al. 2009), with proportional rebates of any excess funds not needed to complete delivery of the final task that is actually delivered.

In a full market approach, buyers would not be restricted just to the 99 participants that we recruited within our research-grant budget to implement this experimental market. We therefore scaled the offers in the workshops upward using an external fund. At the market equilibrium, every dollar contributed by a participant was leveraged with \$10.75 from the research grant funded by the US Department of Agriculture. This approach is equivalent to as if an external donor participated in the structured-donation workshop by contributing a fixed total amount regardless of the quantity or task provided. Importantly, the information about outside source funding was not made known to the participants to avoid stimulating participants to engage in free-riding. The match implies that about 1200 people (or 5 percent of the total population eligible to participate in this study) would contribute in a full auction. This approach remains consistent with our effort to provide a proof-of-concept.

RESULTS

The SWAT simulations reveal that considerable spatial variability of P loading ($\text{kg ha}^{-1} \text{y}^{-1}$) to the reservoir occurs across farms that manage a comparable unit of manure (Fig. 1). The effect of any management project depends on the farm size, location, soil type and other properties of the watershed. This difference across the watershed implies that, when allocating funds, linking market transactions to a science-based model that accounts for the biophysical factors and the process relating manure output at the farm to loading at the reservoir would better assure cost effectiveness.

Seven farmers submitted a total of 13 bids. The simulated P reduction at the reservoir for the bids ranged from less than 1 kg per year for 20 years to nearly 100 kg per year for 20 years. These seven projects were valued in the demand side experiment through Tasks 1 through 4.⁷ The supply curve for the seven most efficient bids illustrates the range of possible market outcomes (Fig. 2). The lowest-cost bid reduced the amount of P reaching the reservoir by about 30 kg P per year for 20 years for a one-time cost of about \$46 per kg, rising to over \$600 per kg on more costly farms (cf. Table 1).

On the demand side, 74% of the 99 participants contributed a positive amount to at least one of the tasks. The demand curve (Fig. 2) is the sum of individual participants' marginal willingness to contribute, scaled by the external fund as mentioned above, for a unit of manure reduced (Fig. 2). Participants revealed a high contribution for initial units of P reduced but the level quickly tapered off.

⁷Other projects (8th through 13th bids in the order of cost effectiveness) which were valued through Tasks 5 and 6 are not included in Figure 2 to show clearly the intersection of the demand and supply curves. All excluded points would be to the right of this figure, farther from the equilibrium.

We used the demand and supply curves to determine the market clearing price (Fig. 2). This resulted in a market-clearing price of \$358 per kg of P reduced per year for 20 years. Combining contributions from the auction and external funds, the first three most cost effective bids (or, equivalently, IPA Task 2 or structured donation Task 1) were funded and are expected to cumulatively reduce about 129 kg of phosphorus per year at the reservoir for 20 years (Table 1).

Per the rules the auction, the market price was set at the level that just exhausted the budget. The budget in this case was the revenue generated from the first three IPA tasks and structured donation task 1 scaled by the external funds. From perspective of the supply side auction, the UPRRA explained previously, the fourth most expensive bid (the fourth bid in Table 1) was the first rejected bid. The revenue beyond the market clearing price was not required and consequently was returned to participants in the demand side auctions in proportion to their offer in that task.

Although comparable prices do not exist, this equilibrium price is lower compared to average costs of phosphorous reduction found in the literature. For example, a study in Pennsylvania found that the cost per kg P reduced by animal waste management (nonpoint source practice) is \$62.05 per year, or \$1241 over 20 years without discounting (Chesapeake Bay Commission 2004). Additionally, a study in Chesapeake Bay finds that the average cost per kg P reduced from a traditional nutrient management plan is \$57.22 per year, or \$1144 over 20 years (Sweeney 2004). The farmers with funded bids were paid \$46,056.70 in total for the reduction determined by our experimental market.

Comparison of two public good mechanisms for the demand side

We anticipated that the revenue potential under the IPA would exceed that under the structured donation treatment, because Smith (2012) and Smith and Swallow (2013) provide evidence that IPA offers can approximate Hicksian marginal willingness to pay. Swallow (2013) discusses the marginal tradeoffs in an IPA-donor's choice to raise his or her bid on a unit by a marginal dollar: a lower bid on the unit increases the chance the unit is not provided and that no additional units are provided, thereby removing additional potential benefits from higher-numbered units. However, a lower bid also lowers the payment that would be due on infra-marginal units that are actually delivered.⁸ However, since neither approach is incentive compatible, the issue requires an empirical evaluation and our results show that the IPA did not raise as much revenue as compared to the simpler, structured donation approach. We examined average contribution across the tasks under the two public good treatments. Our results suggest that participants in the structured donation solicitation workshop contributed higher, on average, than those under the IPA approach across all the tasks. Depending on the task, mean contribution from structured donation was 56% to 104% higher than the IPA approach. The same results hold when we excluded those participants who contributed \$0 for all the tasks. When comparing socio-demographic profiles of

⁸In contrast, the structured donation auction ties the donor's net benefit on units delivered within a particular quantity-range to their choice of the corresponding donation amount. While a low offer could cause the auction to settle and prevent consideration of additional quantity-ranges, the structured auction likely concentrates a donor's opportunity to gain from a lower offer through their choice for that quantity range.

participants across the two treatments, we found that participants under the structured donation treatment had significantly higher income than those under the IPA, while there were no significant differences across the other demographics (Table S1). This may partially explain the discrepancy between the two treatments.

Digging deeper into the contribution behavior across the tasks, Figure 3A shows that the average contribution of participants tended to be relatively constant, although there is a slight increase across the three tasks in the structured donation solicitation Workshop. Average offers from participants in the IPA-based Workshop showed a slight decrease across the six tasks; these trends, however, are not statistically significant. Moreover, we examined “Per unit” contribution across the tasks. “Per unit” contributions remain approximately constant after the IPA task 2 (Figure 3B). While the aggregate contribution across the tasks was approximately constant, tons of cow manure brought under a particular livestock management practice sharply increased from IPA task 1 to IPA task 2 (from about 16 tons to 75 tons of cow manure).

Although participants had different patterns of contribution, both public good treatments produce statistically constant contributions over the range of reduction in P loadings considered in our experiment. This result is consistent with the interpretation that donors act as if there is a constant marginal benefit for each task, despite differences in the quantities associated with each task. We examined the proportion of participants contributing \$1–\$33, \$34–\$66, and \$67–\$100 between the two Workshop-types, and found a statistically significant difference in the proportions across the treatments ($\chi^2=20.35$, df 2, $p<0.0001$); this result was robust to removing the offers of zero contribution from the data ($\chi^2=13.25$, df 2, $p<0.0013$; Figure 3C). This result (Figure 3C) shows that under structured donations, a higher share of individuals contributed higher amounts as compared to IPA, which suggests that average contributions under the structured donations exceeded those under IPA.

We further examined whether participants follow a particular pattern of contribution across the tasks, classifying each participant as having made a constant offer across tasks, increasing their offer on successive tasks, decreasing their offer, or exhibiting a mixed pattern (sometimes increasing their offer between tasks and other times decreasing their offer, Figure 3D). Participants in the structured donations-based Workshop were more likely to exhibit a constant or increasing pattern in their offers ($\chi^2=21.365$, df 3, $p<0.0001$; Figure 3D).

CONCLUSION

Market solutions to environmental problems represent an important opportunity because markets have demonstrated the capacity to bring about efficient outcomes and to drive innovation. At the same time, markets face particular challenges when the environmental “commodity” being supplied is a public good, i.e., subject to the free rider problem, and one that is neither well understood by buyers, nor directly observable.

With an experimental approach, this study developed a local market process for a local public good and demonstrated how an entrepreneur or resource manager could operate as a

market maker. Our experiments compare the performance of the structured donation approach and the IPA, both of which are examples of provision point mechanisms designed to organize contributions by donors in order to facilitate Coasian bargaining and reduce free riding. We believe that the implementation of such a process can potentially play an important role in strengthening the demand side in actual market-like solutions to emission reductions, such as the US acid rain program among many others (e.g., Israel, 2007; Rouse, 2008).

Our findings suggest that, while not incentive-compatible, provision point mechanisms such as the structured donation auctions and the IPA, show promise for increasing participation by buyers in market-like solutions to public good provision. These mechanisms can potentially increase donations to environmental organizations such as the Acid Rain Retirement Fund, which solicits donations to purchase and retire emission allowances as part of the US acid rain market (e.g., Israel, 2007). Provision point mechanisms can reduce free riding by creating a system of mutually leveraged donations, such that donors only pay to the extent that others also pay to support the program. In this sense, these provision point mechanisms work in a manner that is in some ways similar to matching contributions sometimes practiced by corporate donors.

Although the process was new, both consumers and suppliers of improved water quality made actual transactions that supported a local market, suggesting that it can potentially be an effective mechanism for controlling nonpoint pollution. Combining a biophysical model with a reverse auction allows the market maker to allocate financial resources to cost effective and net benefit-enhancing projects.

Our experiment also revealed several major challenges in designing markets for ecosystem services. While 71% of the subjects paid some positive amount in the IPA approach, it did not raise as much revenue as the simpler, structured donation approach. Based on results in this experiment, since donations were higher under the structured process compared to the IPA, we would weakly recommend the structured solicitation approach as preferred over the IPA. However, we generally encourage more research to develop either of these approaches or others to generating revenues for funding public goods through a market-like process that is focused on delivery of a well-specified environmental good (in our case, P reductions).

Moreover, the in-person decision-making setting resulted in a significant logistical challenge indicative of a high transaction costs. These results suggest that other approaches deserve attention in future applications. One possible direction is to use the market approach to reveal society's preferences for environmental improvement, and then couple the revenue from the market with donations or government funding. This way, a market approach can help communities determine how to allocate their limited resources efficiently in a manner that reflects societal preference. Additionally, market makers may use, for example, an internet-based fundraising platform to reduce the market transaction costs, as has been done, for example, with the NutrientNet emissions trading program for Chesapeake Bay administered by the World Resources Institute (e.g., Jones et al, 2000; Ribaud et al, 2010).

Another challenge was in defining the goods and services that are traded in the market. Recent studies in nonmarket valuation emphasize measuring the values of final ecosystem services (Boyd and Banzhaf 2007, Johnston and Russell 2011). In our experiment, we chose ‘tons of cow manure reduced at the reservoir’ as the deliverable sold in the market. While this choice was a result of a series of focus groups which tested alternative measures of water quality, changes in cow manure need to be translated to changes in water quality for the experiment to be scaled up and inform policy. To adapt the preference elicitation mechanism to direct indicators of water quality, cow manure can be replaced with water quality measures, for example, by converting manure to phosphorus using available parameters in the literature, or by simulating the effect of manure input to water quality at some endpoint using a watershed modeling tool. Other alternatives may be appropriate depending on the final ecosystem service. For example, a measure of surface water quality such as changes in P may be appropriate for health or use benefits such as angling or swimming benefits, whereas indicators for biodiversity or relevant species populations may be more appropriate for nonuse benefits. The ecosystem service needs to be carefully defined for each market depending on what benefits from water quality the consumers derive.

In the experience reported here, the SWAT model was used to provide a scientifically legitimate framework for identifying and ranking on-farm manure management projects for impact at the site of interest, the reservoir itself. Importantly, this science-based foundation for judgment was accepted both by farm operators and by public contributors (donors) who made financial decisions leading to the market outcome. However, there is inherent uncertainty in our estimates of changes in phosphorus loading due to the manure management projects and the effects of phosphorus on water quality. This uncertainty could lead to some higher-cost bids for projects being funded in the UPRA over more efficient low-cost projects, which could result in a suboptimal level of water quality and reduced allocative efficiency (Shortle and Horan 2001). However, literature suggests that dealing with this type of uncertainty in managing nonpoint source pollution can be costly. One approach is to use more conservative estimates of effectiveness of conservation projects, but this effectively raises conservation costs (e.g., Wainger et al. 2013). Alternatively, programs may increase research, monitoring, and verification of projects but these activities raise administrative and transaction costs, and may thereby lower market participation (STAC 2013, Walker and Selman 2014). While dealing with this uncertainty is beyond the scope of this paper, alternative science-based frameworks deserve exploration in future work because any market approach depends critically on agreement by participants that items being exchanged are clearly (if imperfectly) defined using a objective standard, in our case based on the SWAT model.

Despite these issues, we argue that using SWAT to understand the impact of farm-specific manure management projects integrates a much-needed scientific framework into markets for water quality. As used, SWAT represents a scientifically legitimate framework for identifying and ranking on-farm manure management projects, or an approximation on which to base the rest of the market mechanism. The present study serves as evidence that market-based transactions integrating both a supply-side (landowner-provider) and a demand-side (consumer-donor) can be facilitated by application of a plausible standard to

transform complex hydro-ecological relationships into the impacts sought by environmental managers and the public constituents or contributors who value improved outcomes delivered cost-effectively.

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Appendix

Text A1 Additional information on the study area and SWAT calibration

The landscape consists of rolling drumlin hills; slopes of greater than 10% are found in about 20% of the basin. Land use/land cover is predominately forested (79%) with light and medium residential (7%) and agriculture (6%) which includes pasture, row crop and orchard land. The surficial geology of the watershed is characterized by glacial till and stratified deposits underlain by bedrock of Devonian and late Proterozoic igneous and metamorphic rock. The maximum storage capacity is 151,400 m³ (Nimiroski and Waldron 2002, Bellet et al. 2003b). The climate is humid continental with 1295 mm of average annual rainfall and monthly average temperatures ranging from 3.5 to 27.3 C°.

Based on mass-balance calculations linked to land use/land cover, P loading rates from most of the sub-watersheds (0.45 kg ha⁻¹ y⁻¹) are relatively low for the Northeast U.S., much closer to natural background values (0.22 kg ha⁻¹ y⁻¹) than loading rates associated with agricultural or urban lands (Reckhow et al. 1980). However, P loading to Moswansicut Reservoir showed higher levels at 1.24 kg ha⁻¹ y⁻¹ (Bellet et al. 2003a). Prompted by algae bloom events, a limnological study was conducted with monthly water quality samples for one summer for the Regulating and Moswansicut reservoirs and found mean summer surface total P concentrations of 12.7 ug l⁻¹ (ESS Group 2011), indicating a lake in a mesotrophic state (Carlson 1977). The Scituate Reservoir has documented a high N:P molar ratio (>25:1), which suggests that P inputs into the reservoir may control primary production and algal growth (Smith 1983). A substantial portion (31.6%) of the biovolume of the phytoplankton

from a study in 2009 was found to be cyanobacteria, primarily *Anabaena plactonica* and *A. flos-aqae*, capable of producing neurotoxins and hepatotoxins (ESS Group 2011).

Peeptoad Brook (USGS 01115098) was used for calibration. The R^2 of simulated vs. measured monthly average streamflow was 0.71 and Nash-Sutcliffe efficiency (NSE) was 0.68, indicating that the model accurately tracked the average monthly flow trends during the simulation period. Validation was then performed using gauge data from the Huntinghouse Brook (USGS 01115110). The R^2 of the simulated versus measured monthly average streamflow for the validation gage is 0.40; the NSE is 0.38, with NSE values between 0 and 1 considered acceptable levels of performance (Moriassi et al. 2007). The calibrated parameters were then applied across the larger Scituate Reservoir Watershed.

Inputs to the SWAT model include twenty years of continuous daily (1994–2010) precipitation and temperature data from the Kingston, RI Weather Station, approximately 35 km from the study area. Geospatial data on soils (SSURGO), hydrography, land use/land cover, and topography (1:24,000 scale) were obtained from the Rhode Island Geographic Information System (RIGIS, <http://www.edc.uri.edu/rigis/>), a raster based GIS. For each livestock operation we incorporated farm specific animal densities and soil P concentrations obtained from field visits to its HRU. Average animal densities were applied to pastures exclusive of bidding farms using data from a Northern Rhode Island Conservation District livestock survey.

To estimate the effects of the two different livestock management practices, we applied an average reduction in loading based on numbers from the Chesapeake Bay Program which estimates best management practice efficiencies based on a literature review as well as professional and expert review [USEPA, 2010, Gitau et al., 2004]. Manure storage was assumed to reduce P loading for a given farm by 80% and water redirection projects were assumed to reduce loading from a given farm by 20%. See [USEPA, 2010]. If both practices were to be implemented, these percentages applied sequentially, in the order of least-cost-per-unit of reduced loading first. We averaged the 20-year SWAT model results to compute an annual marginal reduction in P loading to the reservoir for each farm under practice(s) that farms offered to implement (kg P per year). The calibrated SWAT model was used to simulate the expected annual marginal reduction in P loading to the reservoir for each proposed management practice for each farm (kg P per year), adjusting for the size of the acres credited for the BMP installation.

Text A2. Additional information on the supply-side auction

The two livestock management practices were defined in the following fashion:

Manure Management Storage Area: A well-designed manure storage area prevents harmful nutrients from leaching into soil and waterways. Requirements: (1) Flooring: Reinforced concrete a minimum of 5 in. thick. Based on your anticipated animal count, your minimum recommended pad size is 760 sq. ft.; (2) Siding: Curbs or Siding are required on three of the pad's four sides. They must be a minimum height of 12 in; (3) Covering: Pad must be covered by either a permanent roof, or a durable, removable covering such as a tarp when not being accessed; (4)

Location: Manure storage areas must be placed a minimum of 100 ft. from wells, wetlands, and surface water.

Water Redirection System: Gutters, downspouts and outlet piping installed on barns help redirect water towards lower impact areas. Requirements: (1) Gutters: 0.032 gauge seamless aluminum gutters with a minimum width and depth of 5 in; (2) Downspouts: Downspouts must be a minimum of 3 in. x 4 in. and serve no more than 60 ft. each; (3) Hangers: Hangers must be no more than 24 in. apart on either side; (4) Outlet: Must redirect water away areas of heavy animal usage or waste storage towards lower impact areas. Must be a minimum of 3 in. in diameter if serving 1 downspout or 5 in. in diameter if serving 2 downspouts.

Text A3. Additional information on the demand-side Workshop

Participants for the field experiment were recruited by a commercial recruiting company, Lighthouse Consulting Group, and were adults living in the towns of Scituate, Foster and Gloucester. Recruiting used flyers posted to the town email listserv, town websites, local newsletters, and on-the-ground distribution, as well as posters in public places. Participants gathered at a well-known community meeting hall in Scituate for a two-hour “Water Quality Decision-Making Workshop.” Three sessions were conducted, and each subject participated only in one session. The same moderator led all sessions.

Each session began with a scripted PowerPoint presentation that was designed to give participants a common review and understanding of the linkages between P, manure management, and water quality. This presentation used simple illustrations and clear language, including photographs of a range of potential manure management projects. We were careful about differences in connotation and denotation for our word choices and directly addressed preconceptions and nuances. To ensure understanding, the presenter addressed questions from participants prior to explaining instructions soliciting individuals’ donations or contributions to pay for on-farm manure management projects.

In addition to the PowerPoint presentation, participants were provided with a booklet to review as instructed by the moderator. This booklet contained written instructions for soliciting voluntary contributions under the approach used for that Workshop (IPA or donations), and these instructions were reviewed orally by the moderator as well. The booklet also included a form soliciting offers of contributions; in the IPA workshops individuals made six offers, while in the donations workshops individuals made three offers. Finally, the booklet included a follow-up survey soliciting socio-demographic characteristics of the individual.

All participants were told that there were other Workshops being held in a 2-week period (Oct. 28 – Nov. 12, 2013) and results would depend on the combined choices of participants in these Workshops by explaining that “(s)ome, all, or none of these projects will actually be implemented because of your decisions tonight.” The booklet and the full script for the workshop may be obtained from the authors.

Task 1:

This task includes one water quality project, which would reduce phosphorus in **15.70 tons of cow manure per year** from entering the reservoir. For this task, you have a budget of \$100. Your total contribution cannot be greater than \$100. Please write down your per-ton contribution and the total contribution for the project at the bottom of the page or you may just circle the pre-calculated row.

Price per Ton	Tons of Cow Manure Reduced each year	Your Total Contribution	You would take home
\$0.00	15.70	\$0.00	\$100.00
\$0.50	15.70	\$7.85	\$92.15
\$1.00	15.70	\$15.70	\$84.30
\$1.50	15.70	\$23.55	\$76.45
\$2.00	15.70	\$31.40	\$68.60
\$2.50	15.70	\$39.25	\$60.75
\$3.00	15.70	\$47.10	\$52.90
\$3.50	15.70	\$54.95	\$45.05
\$4.00	15.70	\$62.80	\$37.20
\$4.50	15.70	\$70.65	\$29.35
\$5.00	15.70	\$78.50	\$21.50
\$5.50	15.70	\$86.35	\$13.65
\$6.00	15.70	\$94.20	\$5.80
\$6.40	15.70	~\$100.00	~\$0.00

I would pay \$ _____ per ton to reduce phosphorus in **15.70 tons of cow manure per year** from entering the reservoir. My total contribution is \$ _____ and I would take home \$ _____ (which is **\$100 minus your total contribution**) if the projects in this task were implemented.

Figure A1.

A sample task under individualized price auction (IPA) demand-side experiment.

Table A1

Participants' sociodemographic profiles across the public good treatments

Variables	Description	Public goods treatments	
		Sequential donation (N=30)	IPA(N=69)
		Sample Mean (SD)	Sample Mean (SD)
Male	1 if a participant is male; 0 otherwise	0.43 (0.50)	0.42 (0.49)
Age	Age of participant in years	50.68 (13.81)	48.38 (16.42)
Livestock owner	1 if a participant owns a livestock; 0 otherwise	0.07 (0.26)	0.14 (0.35)
Home owner	1 if a participant owns a home; 0 otherwise	0.83 (0.38)	0.88 (0.32)
Residency	Number of years a participant lived in or around towns of Scituate, Foster or Glocester, RI	19.89 (15.11)	23.96 (16.29)
Lawn-fertilizer user	1 if a participant fertilizes their lawn and garden; 0 otherwise	0.65 (0.49)	0.52 (0.50)
Member	1 if a participant is currently affiliated to any environmental groups or causes; 0 otherwise	0.13 (0.35)	0.22 (0.42)
Graduate degree	1 if a participant has a graduate degree; 0 otherwise	0.13 (0.35)	0.22 (0.42)
Lakes visitor	1 if a participant visited freshwater lakes or streams either for personal enjoyment or recreations in the past 12 months; 0 otherwise	0.83 (0.38)	0.79 (0.41)

Variables	Description	Public goods treatments	
		Sequential donation (N=30)	IPA(N=69)
		Sample Mean (SD)	Sample Mean (SD)
Donate	1 if a participant donated to environmental causes or groups in the past 12 months; 0 otherwise	0.37 (0.49)	0.26 (0.44)
Volunteer	1 if a participant volunteered in environmental projects or causes in the past 12 months; 0 otherwise	0.40 (0.49)	0.28 (0.45)
Income	Participant's total household income	84,913.29 (46,456.98)	65,624.50 (41,427.89)

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Fig. 1. Simulated average annual P loading ($\text{kg ha}^{-1} \text{ y}^{-1}$) of more than 400 hydrologic response units (HRU) to the waters of the Scituate Reservoir system. Results obtained from a 20-year simulation with the spatially-explicit Soil Water Assessment Tool model.

Fig. 2.

The demand curve from the first four tasks in the demand side experiment (blue) and the marginal cost curve for phosphorous reductions from the first seven cost-effective bids in the supply-side auction (red). The intersection of the two curves illustrates the market clearing price. The two demand-side treatments were aggregated to create the demand curve.

Fig 3.

Participants' contribution across tasks in demand-side field experiments. (A) Participants' average contribution for P reduction across tasks, including and excluding \$0 contributors. (B) Participants' average per-unit contribution for P reduction across tasks, including and excluding \$0 contributors. (C) Participants' contribution ranges \$1–\$33, \$34–\$66, and \$67–\$100 across tasks. (D) Pattern of participants' contribution across tasks.

Table 1

Marginal cost and average revenue for phosphorus reduction across Workshop tasks

Ranking of least cost per kg P reduced	Marginal Cost (\$/kg P)	Phosphorus Reduced (kg/year)	Cumulative Phosphorus Reduced (kg/year)	Average Revenue (\$/kg P)	IPA Tasks ^a
1	\$46.37	30.19	30.19		
2	\$276.42	1.85	32.04	1320.81	Task1 (15.70)
3	\$357.11	96.61	128.65	359.27	Task2 (74.90)
4	\$464.78	4.38	133.03		
5	\$489.01	0.81	133.84		
6	\$612.95	6.53	140.36	314.75	Task3 (77.90)
7	\$638.91	7.83	148.19	296.49	Task4 (81.10)
8	\$1,973.05	2.58	150.77	288.23	Task5 (84.90)
9	\$2,749.18	0.22	150.99		
10	\$4,566.46	0.33	151.32		
11	\$10,766.80	0.17	151.48		
12	\$17,755.87	0.53	152.02		
13	\$18,988.52	0.39	152.41	282.67	Task6 (88.70)

^aUnit is “tons of cow manure prevented per year for 20 years”. Six “tasks” under the Individualized Price Auction (IPA) workshops were grouped into three tasks under the structured step-wise donation solicitation by simply merging successive pairs of tasks, meaning IPA Task1 and Task 2 were merged into the first task under donation and so on. Numbers in parentheses show the tons of manure that, if prevented from entering the reservoir directly, would represent an equivalent reduction in P loading in the reservoir.