# Conservation Procurement Auctions with Bidirectional Externalities*

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**Abstract**

This study analyzes a conservation procurement auction with bidirectional externalities, that is, conservation output can affect the costs of individuals dedicated to market production, and vice versa. The procurer observes neither bidders' conversation nor their market efficiency. We show that, under complete information, optimal output is lower with than without negative externalities, as the procurer needs to compensate landowners for their cost increase due to externalities. Under incomplete information, such reduction in optimal output is larger, since the procurer must now provide information rents for landowners to truthfully report both their conservation and market efficiency. We demonstrate that when conservation and market output generate externalities on each other, the above output inefficiencies are emphasized, but ameliorated if the procurer observes either conservation or market efficiency.

Keywords: Mechanism Design, Bidirectional Externalities, Conservation Procurement Auction.

JEL classification: D44, D62, D82, Q15, Q51.

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# 1 Introduction

Procurement auctions are often used to conserve territories rich in biodiversity, or protect endangered species. Examples include the Conservation Reserve Program in the United States (Latacz-Lohmann and Van der Hamsvoort, 1997 and Hellerstein et al., 2015), the Bush Tender Programme in Australia (Stoneham et al., 2003), and the Countryside Stewardship Scheme in the United Kingdom (Dobbs and Pretty, 2004).[1] The participation in a conservation program usually implies the suspension of all market activities and the dedication of the land to conservation, thus requiring a sufficient compensation from the procurer.[2] In addition, the conservation activity can generate externalities on other landowners, potentially increasing (or decreasing) the costs of those who do not dedicate their land to conservation. For instance, Jarrad et al. (2016) analyze a riparian watershed restoration project in Portland, Oregon, showing an increase in home prices of 37% for properties located on the restoration site in the six years following the project, thus reflecting a positive externality from the conservation program to the housing market.[3] Externalities can also stem from non-participants to participants of the conservation program. For example, Leathers and Harrington (2000) study the Conservation Reserve Program, showing that it induces non-participating landowners to expand their production to areas that were not previously cultivated, a phenomenon known as slippage.[4] The main crops in the region analyzed by Leathers and Harrington (2000) are wheat, corn, and grain sorghum. Since these crops require an intense use of pesticides, landowners dedicated to conservation will find it more difficult and expensive to continue their activities.[5] Our paper examines how the existence of negative or positive externalities distorts conservation output in procurement auctions, and its corresponding transfers to landowners.

While several papers analyzed auctions with unidirectional externalities[6], we allow for bidirectional externalities, whereby landowners participating in the conservation program can generate externalities on those dedicated to market activities and vice versa. In this context, a negative (positive) externality from conservation to market activities, increases (decreases, respectively)

[1] As of May 2016, the Conservation Reserve Program has 652,305 contracts with 365,771 farms participating in the program, totaling an annual rental payment of $1.7 billion US$. In the case of the Bush Tender Programme, it signed 586 contracts with 465 landowners from 2001 to 2012, with total payments of $17.51 (million AUS$).

[2] In the Georgia Irrigation Reduction Auction studied by Cummings et al. (2004), farmers suspend irrigation of the land to conserve water for downstream users. In particular, farmers turn their irrigation permit over to the regulator during the drought season in exchange for a one-time lump-sum compensation.

[3] However, properties located 0.5 to 1 km from the restoration site show a mild decrease in property prices of 1% during the same period. Prior studies also found a positive effect of watershed restoration on property prices. Streiner and Loomis (1995), for instance, use a hedonic price model to show that urban stream restoration projects increase property values by 3-13% in California. (The range depends on whether the main benefits of the project are reduced flood damage, revegetation, or enhanced aesthetics.) For other studies finding similar results using contingent valuation methods, see Loomis et al. (2000) and Holmes et al. (2004).

[4] Leathers and Harrington (2000) report slippage for both participating and non-participating landowners. On average, they find an annual slippage of 53% for the 1988-1994 period. Other studies report an average slippage rate of 33% in the period between 1956 and 1985; see Joyce and Skold (1987).

[5] Tegtmeier and Duffy (2004) find that the environmental damage of pesticides on crops amounts to $1.1 billion in 2002 dollars. Together with manure runoff from livestock production, these damages include killing fish, poisoning honeybees, losing predators of pest species, and intoxicating birds.

[6] See Jehiel et al. (1996, 1999 and 2000), Espínola-Arredondo (2008), and Figueroa and Skreta (2011). We elaborate on this literature below.

production costs. Similarly, a negative (positive) externality from market to conservation activities increases (decreases) conservation costs. In addition, the procurer is unable to observe the landowners' efficiency level either in the conservation, the market activity, or both.

We first analyze the case in which the procurer has complete information as our benchmark (observing efficiency levels in both activities for all bidders), and then compare our results with those in the case of incomplete information. In the context of complete information, the negative (positive) externality that the conservation activity imposes on market production increases (decreases) market costs, thus rising (reducing) the procurer's compensation to the affected parties due to their loss in market profits. As a consequence, conservation output becomes more expensive (cheaper) to implement, leading the procurer to decrease (increase) the optimal conservation output level. The previous argument also applies when market production generates externalities on conservation costs.

Under an incomplete information setting, we develop a direct revelation mechanism that induces landowners to truthfully reveal their private information. For comparison purposes, we first present the case in which externalities are absent. As in Myerson (1981), the procurer increases conservation output until its marginal benefit coincides with its virtual marginal cost, where the latter includes information rents. However, in our setting, the regulator has two sources of uncertainty: he does not observe bidders' market nor their conservation efficiency, thus yielding information rents stemming from both unknown parameters. When conservation externalities are present, the procurer must consider not only the virtual marginal costs but also the external effect that every bidder $i$'s conservation output imposes on those producing market goods. Similar to the complete information setting, negative externalities increase landowner $j$'s market cost, thus raising the compensation that the procurer needs to offer to induce full participation.[7] Nonetheless, under incomplete information, the procurer must pay two types of information rents in order to induce truthful revelation of both market and conservation efficiency. Hence, the presence of externalities yields more output inefficiencies when the regulator operates under incomplete than complete information. In other words, the inefficiencies from externalities are emphasized under incomplete information, making our results particularly useful for uninformed regulators seeking to implement conservation programs. As a consequence, the acquisition of information leads to larger efficiency gains when regulators face auctions in which bidders generate externalities than otherwise.

A similar argument applies when landowners dedicated to market activities produce negative externalities which increase the conservation costs of those bidders implementing the conservation program. In this context, the procurer needs to increase the compensation to landowners dedicated to conservation, thus making the program more expensive to implement, ultimately leading the procurer to reduce conservation output. Finally, when both conservation and production externalities coexist, conservation output decreases relative to the case in which only one form of externality

[7] The participation of all landowners helps the uninformed procurer infer their production and conservation efficiencies, thus allowing for an efficient assignment of output levels in the direct revelation mechanism. The opposite argument applies in the case of positive externalities, where landowner $i$'s conservation output decreases landowner $j$'s market cost, thus reducing the procurer's compensation.

is present. In addition, we examine optimal output when the procurer observes both market and conservation efficiency, only one of these, or none; showing that, as he becomes less informed, the bidders' information rents increase, inducing the procurer to decrease conservation output.

We also identify optimal transfers, which depend on every bidder's virtual conservation cost and the contingent market profit he would have obtained should he continue his market activities (foregone profits). Hence, both components of the transfers are affected by externalities. In particular, when negative conservation externalities are present, first, every bidder's virtual conservation cost decreases as his conservation output is lower under externalities; and, second, if he were to continue his market activity, he would suffer a negative externality from those bidders dedicated to conservation, thus reducing his contingent market profit. Therefore, every bidder's transfer is lower with than without externalities since both costs and outside options are lower when this type of externality is present. Finally, a similar argument applies under negative production externalities, since the procurer implements a smaller conservation output, which ultimately decreases every bidder $i$'s virtual conservation costs.

Our results could help procurers designing conservation programs in areas with little information about landowners' conservation costs, or about their current market efficiency, when bidirectional externalities exist. Similarly, our model extends to the procurement of utility contracts, in regions where competing firms have no prior experience delivering such utility (e.g., building companies seeking to obtain a water treatment and distribution contract). In that setting, bidirectional externalities could arise if, for instance, water treatment improves health conditions on the region, thus increasing labor productivity of those firms still dedicated to market activities and, in addition, polluting market activities raise the costs of the water company. In addition, our findings shed some light about the consequences of ignoring one or both types of externalities. For instance, if the regulator considers a negative externality from conservation to market activities (but ignores externalities from market to conservation), we show that the conservation output is excessive (insufficient) when the externality he ignores is negative (positive, respectively). Therefore, the conservation program would be too aggressive as it hurts market activities, or too passive as it jeopardizes biodiversity.

**Related literature.** Several papers have analyzed the effects of negative externalities on auctions. For instance, Jehiel et al. (1996, 1999 and 2000) and Figueroa and Skreta (2011) consider that a bidder's payoff from not participating in the auction (or participating but not winning the object) is affected by who gets the object.[8] Espinola-Arredondo (2008) assumes that bidders' payoffs have two components, revenue and costs, where only costs are being affected by externalities. In particular, she considers that the production cost of those bidders losing the auction is affected not only by the identity of the winner but also by the output decision (namely, conservation level) of the winning bidder.[9] Similarly, our paper considers that externalities affect the bidders'

[8] Filiz-Ozbay and Ozbay (2007) study an externality created by the bidder to herself, and Bartling and Netzer (2016) experimentally analyze players' motives to affect other players' monetary payoffs.

[9] In addition, she considers that only a single efficiency parameter is unobserved by the procurer, while our model

conservation/production cost. However, we examine bidirectional externalities: those produced by the winning bidders developing the conservation program, and also by the losing bidders still operating in the market.

Hansen (1988), Desgagne (1988) and Dasgupta and Spulber (1990) examine two-dimensional bid auctions.[10] In addition, Che (1993) studies a score-based system of two-dimensional bid auctions (quality, price) in order to implement an optimal mechanism, and Branco (1997) also analyzes a multidimensional bid auction, but considers the impact of costs' correlation on the design of multidimensional mechanisms. Similarly, we examine a direct revelation mechanism in which every bidder truthfully reveals his two-dimensional type, efficiency in conservation and in market activities, since the former affects the bidder's ability to generate conservation while the latter increases the compensation that the procurer needs to offer to achieve participation.

Finally, several authors have analyzed procurement auctions for environmental investments, since they are considered to be more cost-efficient than uniform-rate payment schemes.[11] This is mainly due to the heterogeneity of conservation benefits and costs across different parcels of land (Latacz-Lohmann and Van der Hamsvoort, 1997), despite of the fact that auctions entail information rents that participating bidders receive and higher administrative costs; see Kirwan et al. (2005) and Connor et al. (2008). Additionally, studies have shown that uniform-rate payment schemes are prone to adverse selection problems, since they attract landowners with low market efficiencies (e.g., poor soil quality) who may not be the most efficient in conservation; see Osterberg (2001), Hynes and Garvey (2009), and Quillérou et al. (2010). Our paper focuses on a procurement auction as a tool to promote biodiversity where, in addition, we allow for externalities to affect both the costs of landowners producing conservation and those who continue their market activities.

Our paper is structured as follows. Section 2 develops the model, Section 3 analyzes output and transfers under complete information, while section 4 examines them under incomplete information. Section 5 discusses our main results and conclusions.

## 2 Model

Consider $N$ landowners producing a homogenous market good. In order to promote biodiversity, the regulator conducts a procurement auction. When landowner $i$ implements a conservation project, he dedicates the land to a predefined environmental service, such as biodiversity enrichment, and refrains from alternative land use activities, such as market production. Let $\theta_i^K$ denote landowner $i$'s efficiency, where superscript $K = \{C, M\}$ represents conservation or market production, respectively. Efficiency parameter $\theta_i^K$ is only observable to landowner $i$, but its distribution, $\theta_i^K \sim F_i^K \left[\underline{\theta}_i^K, \overline{\theta}_i^K\right]$, is common knowledge. For simplicity, we assume that the production and

allows for two parameters (conservation and market efficiency).

[10] Bichler (2000) experimentally examines multi-attribute auctions, and Asker and Cantillon (2010) study a procurement auction considering price and quality. For a literature review, see Rochet and Stole (2003).

[11] Costa Rica's Payments for Environmental Services and Mexico's Payments for Hydrological Environmental Services are examples of uniform-rate payment schemes; for more details see Wunder et al. (2008).

conservation efficiency parameters are independent of each other. In addition, our model allows for market production to generate a positive or negative externality on conservation, and vice versa; thus allowing for bidirectional externalities.

The utility of landowner $i$ from activity $K$ is

$$u_i^K\left(q_i^K,\theta_i^K\right)=t_i^K\left(q_i^K\right)-C_i^K\left(q_i^K,q_{-i}^J,\theta_i^K\right) \tag{1}$$

When landowner $i$ produces $q_i^M$ units of the market good, he receives a market revenue of $t_i^M\left(q_i^M\right)=pq_i^M$, where $p>0$ denotes a given price. If instead, landowner $i$ produces $q_i^C$ units of conservation, the transfer that he receives from the procurer is $t_i^C\left(q_i^C\right)$ which is a function of his conservation output $q_i^C$. In addition, the second term in expression (1), $C_i^K\left(q_i^K,q_{-i}^J,\theta_i^K\right)$, represents landowner $i$'s cost, which is a function of (i) his own output $q_i^K$; (ii) the externalities that activity $J\neq K$ of other landowners impose on him as described by the vector $q_{-i}^J\equiv\left(q_i^J,...,q_{i-1}^J,q_{i+1}^J,...,q_N^J\right)$; and (iii) his efficiency in activity $K$, $\theta_i^K$. Finally, when $q_i^K=0$, costs are nil, $C_i^K\left(0,q_{-i}^J,\theta_i^K\right)=0$ for all $q_{-i}^J$ and $\theta_i^K$.

## 2.1 Assumptions

We next describe how landowner $i$'s total cost in activity $K$, $C_i^K$, and his marginal cost, $MC_i^K\equiv\frac{\partial C_i^K}{\partial q_i^K}$, are affected by his output decisions and efficiency.

**Assumption 1.** *Total and marginal costs of landowner $i$ in activity $K$ increase in his own output level, i.e., $\frac{\partial C_i^K}{\partial q_i^K},\frac{\partial MC_i^K}{\partial q_i^K}\geq 0$. These costs are, however, decreasing in his own efficiency, i.e., $\frac{\partial C_i^K}{\partial \theta_i^K},\frac{\partial MC_i^K}{\partial \theta_i^K}\leq 0$; at a decreasing rate $\frac{\partial^2 C_i^K}{\partial(\theta_i^K)^2},\frac{\partial^2 MC_i^K}{\partial(\theta_i^K)^2}\geq 0$; and $\frac{\partial^2 MC_i^K}{\partial q_i^K\partial\theta_i^K}\leq 0$.*

Hence, the single-crossing condition holds since $\frac{\partial MC_i^K}{\partial \theta_i^K}\leq 0$; and the last part of assumption 1 states that the convexity of the cost function decreases as landowner $i$ becomes more efficient. Given the similarities that negative and positive externalities impose on costs, we next present our assumptions for the case of negative externalities, and at the end of this subsection discuss the main differences with positive externalities. The following assumption describes how total and marginal costs are affected by negative externalities.

**Assumption 2.** *Total and marginal costs of landowner $i$ increase in the negative externalities that landowner $j\neq i$ imposes on him, i.e., $\frac{\partial C_i^K}{\partial q_j^J},\frac{\partial MC_i^K}{\partial q_j^J}\geq 0$. These are attenuated by his own efficiency, that is, $\frac{\partial\left(\frac{\partial C_i^K}{\partial q_j^J}\right)}{\partial\theta_i^K},\frac{\partial\left(\frac{\partial MC_i^K}{\partial q_j^J}\right)}{\partial\theta_i^K}\leq 0$.*

Hence, total and marginal cost increase with negative externalities, and such effects diminish in landowner $i$'s own efficiency. When he is relatively inefficient in activity $K$, a given increase in negative externalities, $q_j^J$, yields a large increase in his cost. However, when he is relatively efficient, such an increase is minor.

**Assumption 3.** *The effect of externalities on landowner i's cost increase in the output generated by other landowners* $j \neq k \neq i$, *i.e.,* $\frac{\partial^2 C_i^K}{\partial (q_j^J)^2} \geq 0$ *and* $\frac{\partial^2 C_i^K}{\partial q_j^J \partial q_k^J} \geq 0$. *These effects are attenuated by the efficiency of landowner i, that is,* $\frac{\partial\left(\frac{\partial^2 C_i^K}{\partial (q_j^J)^2}\right)}{\partial \theta_i^K}, \frac{\partial\left(\frac{\partial^2 C_i^K}{\partial q_j^J \partial q_k^J}\right)}{\partial \theta_i^K} \leq 0.$

Intuitively, not only landowner $i$'s costs increase in landowner $j$'s production, but at an increasing rate, thus reflecting that $i$'s costs are convex in negative externalities, as depicted in Figure 1.[12] Also, the efficiency of landowner $i$ attenuates the convexity of his cost function. In order to illustrate our model and results, we next present a parametric example, which is further developed throughout the paper.

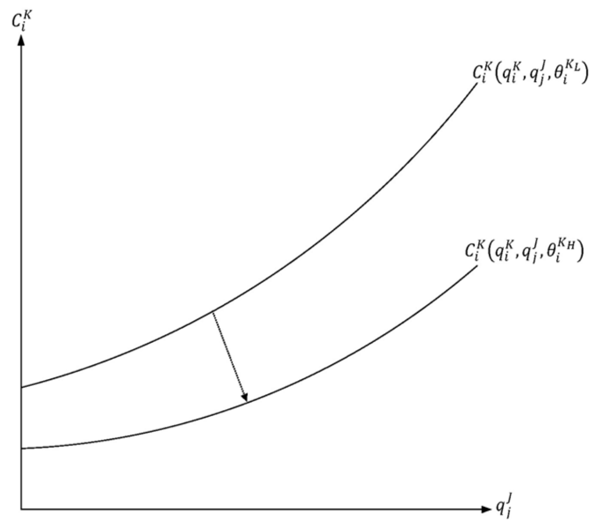


Fig 1. Effect of externalities on total and marginal costs.

**Example 1.** Consider cost function

$$C_i^K\left(q_i^K, q_{-i}^J, \theta_i^K\right) = \frac{q_i^K\left(q_i^K + \alpha^J \sum_{j \neq i} q_j^J\right)}{1 + \theta_i^K}$$

for activity $K$. Following Jehiel et al. (1996), $\alpha^J \geq 0$ measures the intensity of the negative externality from all other $N-1$ landowners dedicated to activity $J \neq K$.[13] Let us next examine Assumptions 1-3. In particular, the marginal cost is $MC_i^K = \frac{1}{1+\theta_i^K}\left(2q_i^K + \alpha^J \sum_{j \neq i} q_j^J\right)$ which

[12] For illustration purposes, Figure 1 considers two efficiency levels $\theta_i^{K_L}$ and $\theta_i^{K_H}$ which represent low and high levels of efficiency respectively, satisfying $\theta_i^{K_L} < \theta_i^{K_H}$.

[13] For simplicity, this functional form assumes that the intensity of negative externality is symmetric across landowners. The externality that each of them experiences can, however, be different if output levels are different, that is, $\alpha^J \sum_{j \neq i} q_j^J \neq \alpha^J \sum_{j \neq k} q_k^J$ for two landwoners $i$ and $k$.

is unambiguously positive and increasing in output. Furthermore, total and marginal costs are decreasing in efficiency $\theta_i^K$ at a decreasing rate, i.e., $\frac{\partial C_i^K}{\partial \theta_i^K} = -\frac{q_i^K}{\left(1+\theta_i^K\right)^2}\left(q_i^K + \alpha^J \sum_{j\neq i} q_j^J\right) \leq 0$, $\frac{\partial^2 C_i^K}{\partial \left(\theta_i^K\right)^2} = \frac{2q_i^K}{\left(1+\theta_i^K\right)^3}\left(q_i^K + \alpha^J \sum_{j\neq i} q_j^J\right) \geq 0$, $\frac{\partial MC_i^K}{\partial \theta_i^K} = -\frac{1}{\left(1+\theta_i^K\right)^2}\left(2q_i^K + \alpha^J \sum_{j\neq i} q_j^J\right) \leq 0$ and $\frac{\partial^2 MC_i^K}{\partial \left(\theta_i^K\right)^2} = \frac{2}{\left(1+\theta_i^K\right)^3}\left(2q_i^K + \alpha^J \sum_{j\neq i} q_j^J\right) \geq 0$. Assumption 2 is also satisfied given that landowner $i$'s total and marginal costs (weakly) increase in other landowners' output, $\frac{\partial C_i^K}{\partial q_j^J} = \frac{\alpha^J q_i^K}{1+\theta_i^K} \geq 0$ and $\frac{\partial MC_i^K}{\partial q_j^J} = \frac{\alpha^J}{1+\theta_i^K} \geq 0$; which are attenuated in landowners $i$'s efficiency, $\theta_i^K$. Finally, Assumption 3 weakly holds due to the linearity of the cost function in externalities, that is, $\frac{\partial^2 C_i^K}{\partial (q_j^J)^2} = \frac{\partial^2 C_i^K}{\partial q_j^J \partial q_k^J} = 0$. □

We next study the market activity of landowner $i$. (All proofs are relegated to the appendix.)

**Lemma 1**. *Landowner $i$ chooses an optimal market output, $q_i^{M*}$, that maximizes (1) which solves*

$$p = \frac{C_i^M\left(q_i^{M*}, q_{-i}^C, \theta_i^M\right)}{\partial q_i^M} \tag{2}$$

*which is independent of others' market output. In addition, $q_i^{M*}$ and market profit, $U_i^M\left(q_i^{M*}, \theta_i^M\right)$, increase in landowner $i$'s production efficiency, $\theta_i^M$.*

**Remark**. In the case of positive externalities, landowner $i$'s total and marginal costs decrease in other landowner's output; and such a decrease is attenuated by landowner $i$'s own efficiency. In addition, landowner $i$'s costs are convex in externalities. That is, having received a certain level of positive externality from landowner $j$, landowner $i$ does not have that much room for further cost reduction upon a higher level of externality from landowner $j$ (or another positive externality from landowner $k$.)[14]

**Social Welfare.** The welfare that landowner $i$ generates when producing conservation output $q_i^C$ is

$$W_i\left(q_i\right) = V\left(q_i^C\right) - (1+\lambda)\, t_i^C\left(q_i^C\right) \tag{3}$$

where $V\left(q_i^C\right)$ denotes the value that the procurer assigns to conservation, which is increasing and concave in $q_i^C$; and $\lambda \geq 0$ represents the shadow cost of raising public funds. In addition, let $\theta_i = \left(\theta_i^M, \theta_i^C\right)$ be landowner $i$'s efficiency pair, where $\theta_i^M \in \Theta^M$ and $\theta_i^C \in \Theta^C$; and $\theta \equiv (\theta_1, \ldots, \theta_N)$ be the efficiency profile for all landowners, such that $\theta \in \Theta$ where $\Theta$ is the Cartesian product $\Theta^M \times \Theta^C$. Since the procurer does not observe $\theta$, he takes the expected welfare from each landowner

[14] If landowner $j$ imposes a positive externality while landowner $k$ generates a negative externality, then the two externalities attenuate each other, entailing that landowner $i$'s costs can increase or decrease, depending on which effect dominates.

$i$, $W_i(q_i)$, and sums over all landowners, that is,

$$EW\left(q^C, t^C\right) = \sum_{i=1}^{N} \beta_i E_\theta \left[W_i\left(q_i\right)\right] \tag{4}$$

where $\beta_i$ denotes the weight the procurer assigns to landowner $i$, subject to $0 < \beta_i \leq 1$ and $\sum_{i=1}^{N} \beta_i = 1$; while $q^C \equiv \left(q_1^C, \ldots, q_N^C\right)$ and $t^C \equiv \left(t_1^C, \ldots, t_N^C\right)$ represent the profile of conservation output and transfer, respectively.

# 3 Complete information

As a benchmark for future comparisons, we next describe the optimal contract (i.e., output and transfer profiles) under complete information. For compactness, let $MB_i^C \equiv \frac{\partial V\left(q_i^C\right)}{\partial q_i^C}$ represent the marginal benefit from the additional unit of conservation output; $MC_i^C \equiv \frac{\partial C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)}{\partial q_i^C}$ denote the marginal conservation cost of landowner $i$; and, $MEC_i \equiv \sum_{j \neq i} \frac{\beta_j}{\beta_i} \frac{\partial C_j^M\left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right)}{\partial q_i^C}$ represent the marginal external cost that landowner $i$'s conservation output imposes on other landowners' costs.

**Lemma 2 [Complete information].** *When the procurer observes every landowner $i$'s efficiency pair $\theta_i = \left(\theta_i^C, \theta_i^M\right)$, he chooses the conservation output $q_i^{C**}$ that solves*

$$MB_i^C = (1+\lambda)\left[MC_i^C - MEC_i\right]. \tag{5}$$

*In addition, the transfer to landowner $i$ is*

$$t_i^{C**}\left(q_i^{C**}\right) = C_i^C\left(q_i^{C**}, q_{-i}^{M**}, \theta_i^C\right) + \left[p\hat{q}_i^M - C_i^M\left(\hat{q}_i^M, q_{-i}^{C**}, \theta_i^M\right)\right]$$

*where $\hat{q}_i^M$ denotes the contingent market output of landowner $i$ that solves (2).*

Hence, under no externalities, $MEC_i$ becomes nil, and the procurer chooses landowner $i$'s output by solving $MB_i^C = (1+\lambda)MC_i^C$, i.e., balancing the marginal value of additional conservation output and its marginal conservation cost, which yields $q_i^{C**}$. However, when negative (positive) conservation externalities are present, $MEC_i$ is negative (positive) since landowner $i$'s output increases (decreases) the production costs of other landowners, entailing that $(1+\lambda)\left[MC_i^C - MEC_i\right]$ lies above (below, respectively) $(1+\lambda)MC_i^C$. As a consequence, the presence of negative (positive) conservation externalities induces a smaller (larger) optimal output than when externalities are absent; as depicted in figure 2. Similarly, if only production externalities exist, i.e., from landowners dedicated to market activities to those doing conservation, landowner $i$'s marginal conservation cost increases, which reduces his optimal conservation output.

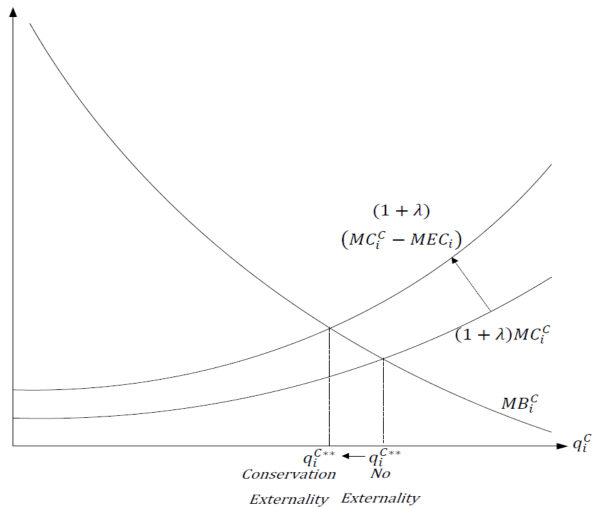


Fig 2. Complete information, with and without externalities.

**Example 2.** Continuing our above parametric example, we can now evaluate expression (5), assuming that the procurer assigns a value $V\left(q_i^C\right) = q_i^C$ to conservation output, where $\beta_i = 1$ for every landowner $i$. For simplicity, we assume that $\theta_i^K \in [0,1]$ for every landowner $i$ and for every activity $K$. In a setting with two landowners, we need to find $MEC_i$ evaluated at the profit-maximizing market output solving (1), i.e., $p = \frac{2\hat{q}_i^M + \alpha^C q_j^C}{1+\theta_i^M}$ which yields $\hat{q}_i^M = \frac{p\left(1+\theta_i^M\right) - \alpha^C q_j^C}{2}$, where the optimal contingent market output of landowner $i$ is affected by the conservation externalities from landowner $j$. This output entails a contingent market cost of $C_i^M\left(\hat{q}_i^M, q_j^C, \theta_i^M\right) = \frac{\left[p\left(1+\theta_i^M\right) - \alpha^C q_j^C\right]\left[p\left(1+\theta_i^M\right) + \alpha^C q_j^C\right]}{4\left(1+\theta_i^M\right)}$. The first-order derivative of this cost for landowner $j$, $C_j^M\left(\hat{q}_j^M, q_i^C, \theta_j^M\right)$, with respect to $q_i^C$ yields $MEC_i = -\frac{\left(\alpha^C\right)^2}{2\left(1+\theta_j^M\right)} q_i^C$. In that setting, expression (5) becomes

$$1 = (1+\lambda)\left[\frac{2q_i^C + \alpha^M q_j^M}{1+\theta_i^C} - \left(-\frac{\left(\alpha^C\right)^2}{2\left(1+\theta_j^M\right)} q_i^C\right)\right] \tag{6}$$

since $MC_i^C = \frac{2q_i^C + \alpha^M q_j^M}{1+\theta_i^C}$. Simultaneously solving (6) and $\hat{q}_j^M = \frac{p\left(1+\theta_j^M\right) - \alpha^C q_i^C}{2}$, we obtain

$$q_i^{C**} = \frac{\left(1+\theta_j^M\right)\left[\alpha^M (1+\lambda)\left(1+\theta_j^M\right)p - 2\left(1+\theta_i^C\right)\right]}{(1+\lambda)\left[\alpha^M \alpha^C \left(1+\theta_j^M\right) - 4\left(1+\theta_j^M\right) - \left(\alpha^C\right)^2\left(1+\theta_i^C\right)\right]}$$

which is lower when externalities are present than absent.[15] $\square$

[15] In particular, $\left.\frac{\partial q_i^{C**}}{\partial \alpha^K}\right|_{\alpha^K=0} \leq 0$ for all $K = \{C, M\}$ since $\theta_i^C \in [0,1]$ by definition.

# 4 Incomplete information

As described in the previous sections, the procurer does not observe efficiency parameters, and uses a Direct Revelation Mechanism (DRM) to solve equation (4).[16] In particular, in a DRM the procurer asks each landowner $i$ to report his production and conservation efficiency, $\theta_i = \left(\theta_i^M, \theta_i^C\right) \in \Theta$, such that the procurer can choose the conservation and transfer profile $\left(q^C, t^C\right)$ to solve

$$\max_{q^C, t^C} EW\left(q^C, t^C\right)$$

subject to:

1. Bayesian Incentive Compatibility:

$$U_i^C\left(\theta_i^C, \theta_i^C\right) \geq U_i^C\left(\hat{\theta}_i^C, \theta_i^C\right) \quad \text{for all } \; \theta_i^C, \hat{\theta}_i^C \in \Theta^C \; \text{ where } \hat{\theta}_i^C \neq \theta_i^C \tag{7}$$

$$U_i^M\left(\theta_i^M, \theta_i^M\right) \geq U_i^M\left(\hat{\theta}_i^M, \theta_i^M\right) \quad \text{for all } \; \theta_i^M, \hat{\theta}_i^M \in \Theta^M \; \text{ where } \hat{\theta}_i^M \neq \theta_i^M \tag{8}$$

2. Individual Rationality:

$$U_i^C\left(\underline{\theta}_i^C\right) \geq U_i^M\left(\overline{\theta}_i^M\right) \tag{9}$$

Conditions (7) and (8) imply that landowner $i$ truthfully reveals his conservation efficiency, $\theta_i^C$, and production efficiency, $\theta_i^M$, respectively, when taking expectation of other landowners' efficiency into account. Condition (9) implies that, even if landowner $i$ is the least efficient in conservation and the most efficient in production, he still has incentives to participate. Hence, any other landowner, who is more efficient in conservation or less efficient in production, will also participate. Before solving the DRM, we present two definitions.

**Definition 1.** *Let* $VMC_i^C \equiv \frac{\partial \tilde{C}_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)}{\partial q_i^C}$ *be the Virtual Marginal Conservation Cost of landowner i, where*

$$\tilde{C}_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right) \equiv C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right) - \frac{1 - F_i^C\left(\theta_i^C\right)}{f_i^C\left(\theta_i^C\right)} \frac{\partial C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)}{\partial \theta_i^C}$$

*represents his virtual conservation cost.*

In particular, $\tilde{C}_i^C(\cdot)$ comprises his actual conservation cost, $C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)$, and his information rent, $-\frac{1-F_i^C\left(\theta_i^C\right)}{f_i^C\left(\theta_i^C\right)} \frac{\partial C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)}{\partial \theta_i^C} \geq 0$, to truthfully reveal $\theta_i^C$; as in Myerson (1981). Hence, $VMC_i^C$ can also be expressed as $VMC_i^C = MC_i^C - \frac{1-F_i^C\left(\theta_i^C\right)}{f_i^C\left(\theta_i^C\right)} \frac{\partial^2 C_i^C(\cdot)}{\partial \theta_i^C \partial q_i^C}$, which by the single-crossing property entails that $VMC_i^C > MC_i^C$.

[16] If the government owned the land to be dedicated to conservation, it would observe its cost efficiency, thus, reducing the mechanism to one in which only market costs are unknown. We analyze this mechanism in section 4.2.

**Definition 2.** *Let* $VEC_i \equiv \sum_{j \neq i} \frac{\beta_j}{\beta_i} \frac{\partial \tilde{C}_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right)}{\partial q_i^C}$ *be the Virtual External Cost of landowner i, which is the weighted sum of his marginal external effect on the virtual contingent production costs of landowners* $j \neq i$ *if the procurer also chooses them for conservation, and thus they produce the contingent market output,* $\hat{q}_j^M$*, where*

$$\tilde{C}_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right) \equiv C_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right) + \frac{F_j^M \left(\theta_j^M\right)}{f_j^M \left(\theta_j^M\right)} \frac{\partial C_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right)}{\partial \theta_j^M}$$

*represents landowner j's virtual contingent production cost.*

Specifically, $\tilde{C}_j^M (\cdot)$ comprises the actual production cost, $C_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right)$, and the information rent, $\frac{F_j^M \left(\theta_j^M\right)}{f_j^M \left(\theta_j^M\right)} \frac{\partial C_j^M \left(\hat{q}_j^M, q_{-j}^C, \theta_j^M\right)}{\partial \theta_j^M}$. Therefore, $VEC_i$ can be expressed as $VEC_i = MEC_i + \sum_{j \neq i} \frac{\beta_j}{\beta_i} \frac{F_j^M \left(\theta_j^M\right)}{f_j^M \left(\theta_j^M\right)} \frac{\partial^2 C_j^M (\cdot)}{\partial \theta_j^M \partial q_i^C}$, which by assumption 2 entails that $MEC_i > VEC_i$. Hence, landowners $j \neq i$ require an information rent to truthfully reveal their types, which increases the procurer's cost of implementing output $q_i^C$ due to his lack of information.

## 4.1 Optimal output profile

We next show that using the Revelation Principle, the DRM is implementable; and find the optimal output levels that the procurer assigns to each landowner.

**Proposition 1**. *The DRM truthfully implements the social welfare function* $EW(\cdot)$ *in Bayesian Nash Equilibrium, yielding an optimal output profile* $q^* = (q_1^*, \ldots, q_N^*)$*, where every landowner i's market output is* $q_i^{M*} = 0$*, and his conservation output,* $q_i^{C*}$*, solves*

$$MB_i^C = (1 + \lambda) \left[VMC_i^C - VEC_i\right] \tag{10}$$

*if* $\theta_i^C \geq \tilde{\theta}_i^C \left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$*. Otherwise, landowner i keeps its market production as described in Lemma 1. In addition, the optimal conservation output* $q_i^{C*}$ *increases in landowner i's own conservation efficiency,* $\theta_i^C$*.*

We next analyze the optimal conservation output of landowner $i$ arising from Proposition 1. For illustration purposes, we first present the case in which externalities are absent; then the case in which conservation externalities are present; and finally the setting where both conservation and production externalities exist.

### 4.1.1 Benchmark - Incomplete information without externalities

Under incomplete information, the procurer does not observe $MC_i^C$ but constructs the virtual marginal cost $VMC_i^C$, which includes the information rent to landowner $i$. Hence, in the case of no externalities, $VEC_i$ is absent from expression (10), and the procurer chooses conservation output as the following Corollary describes.

**Corollary 1 [No externalities, Myerson (1981)].** *When externalities are absent and the procurer does not observe every landowner i's efficiency pair* $\theta_i = \left(\theta_i^C, \theta_i^M\right)$*, he chooses a market output of* $q_i^{M_0^*} = 0$*, and a conservation output* $q_i^{C_0^*}$ *that solves*

$$MB_i^C = (1+\lambda)VMC_i^C$$

*if* $\theta_i^C \geq \tilde{\theta}_i^C\left(\theta_i^M\right)$*. Otherwise, landowner i keeps its market production as described in Lemma 1.*

Therefore, as in standard mechanism design problems without externalities, the procurer equates the marginal benefit with the virtual marginal cost; as illustrated in Figure 3a. When landowner $i$'s conservation efficiency is the highest, $\overline{\theta}_i^C$, his conservation costs are lower than those of all other landowners, implying that information rents are nil, i.e., $F_i^C(\overline{\theta}_i^C) = 1$ entailing $\frac{1-F_i^C(\overline{\theta}_i^C)}{f_i^C(\overline{\theta}_i^C)} = 0$ ("no distortion at the top"). In contrast, when $\underline{\theta}_i^C \leq \theta_i^C < \overline{\theta}_i^C$, the procurer induces participation by paying an information rent. This is illustrated in Figure 3a, where the information rent is depicted by the shaded area between $(1+\lambda)VMC_i^C$ and $(1+\lambda)MC_i^C$. Hence, the output under incomplete information, $q_i^{C_0^*}$, is lower than under complete information, $q_i^{C**}$.

However, when his market efficiency is the lowest, $\underline{\theta}_i^M$, his production cost cannot be further increased. Therefore, $F_i^M(\underline{\theta}_i^M) = 0$, entailing that the landowner extracts no information rent; see Definition 2. This is called "no distortion at the bottom," implying that his actual and virtual production costs coincide. Whereas for $\underline{\theta}_i^M < \theta_i^M \leq \overline{\theta}_i^M$, the landowner captures an information rent, which is represented by the shaded area between the actual and virtual marginal production cost; as depicted in Figure 3b. As shown in the figure, output under incomplete information is larger than under complete information, i.e., $q_i^{M_0^*} > q_i^{M**}$. Hence, the total revenue that the landowner obtains under incomplete information is larger, thus implying a higher compensation to implement the conservation program.

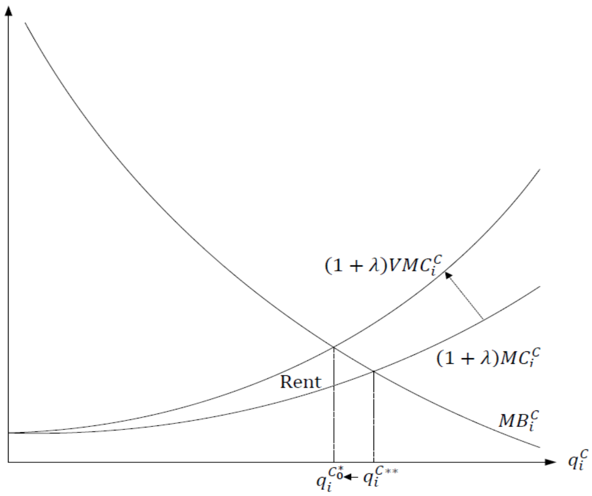


Fig 3a. Information rent in conservation.

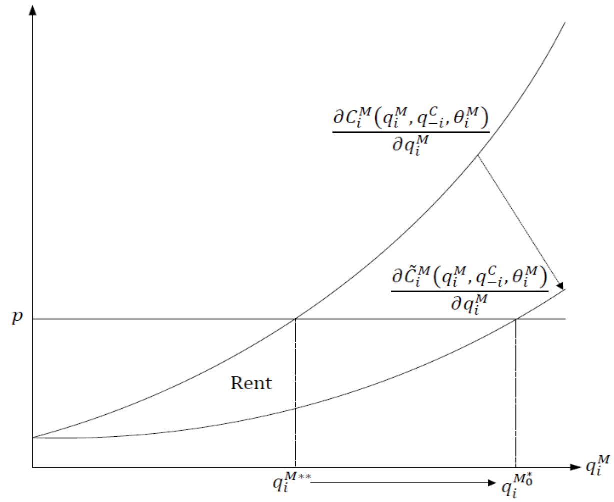


Fig 3b. Information rent in market activities.

#### 4.1.2 Introducing Externalities

**Conservation Externalities.** If, however, landowner $i$ imposes negative conservation externalities on landowners dedicated to market activities, $VEC_i$ becomes negative. Intuitively, landowner $i$'s externality increases the marginal virtual costs for market output of other landowners. Figure 4a depicts the optimal conservation output without and with negative conservation externalities. Under no externalities, the marginal benefit and $VMC_i^C$ functions cross at conservation output $q_i^{C_0^*}$. In the presence of negative conservation externalities, however, the $\left(VMC_i^C - VEC_i\right)$ curve lies above the $VMC_i^C$ curve which, because of the concavity of the benefit function, entails a lower conservation output than that in the absence of externalities. Relative to the case of no externalities, the procurer now faces higher costs, since landowner $j$'s market cost increases, thus raising the compensation that the procurer needs to offer to induce full participation. Hence, the procurer sets a lower conservation output when negative conservation externalities are present than otherwise. (The opposite argument applies in the case of positive externalities.) In summary, under no externalities, landowner $i$ produces $q_i^{C_0^*}$ with conservation cost of $C_1 + E_1$ and welfare of $A_1 + B_1 + D_1$. With negative externalities on others, his conservation output decreases to $q_i^{C_1^*}$ and costs change to $C_1 + B_1$. Area $B_1$ represents the increase in production cost that other landowners experience from landowner $i$'s output. That is, for these landowners to participate, the procurer needs to compensate them with a more generous transfer than under no externalities.

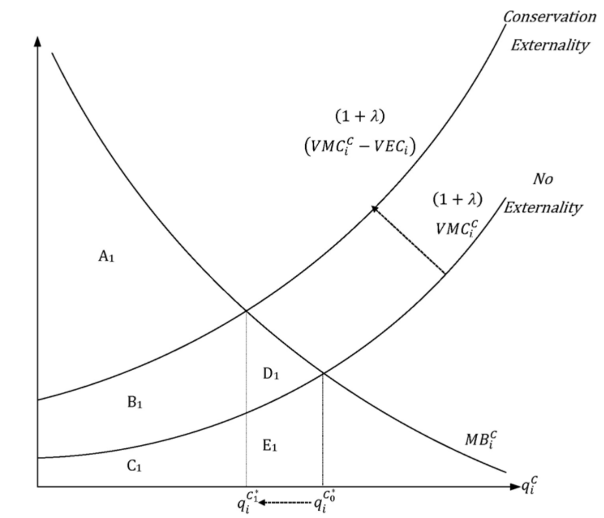


Fig 4a. Negative conservation externalities from $i$.

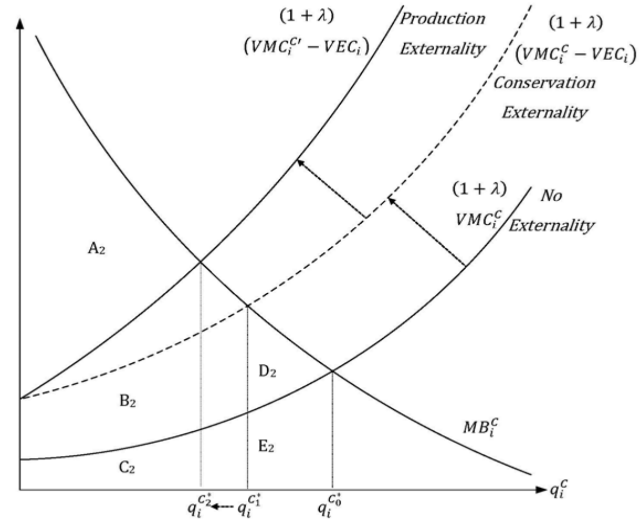


Fig 4b. Negative production externalities to $i$.

**Production Externalities.** If the market activities of other landowners impose negative externalities on landowner $i$, his marginal cost increases, implying that $VMC_i^C$ would also increase; ultimately increasing the right-hand side of (10). Figure 4b depicts this case, showing that, since $VMC_i^{C\prime} > VMC_i^C$, optimal conservation is smaller with than without production externalities. (The opposite result applies if market production generates positive externalities on the costs of landowners dedicated to conservation, where $VMC_i^{C\prime} < VMC_i^C$, thus entailing a higher conservation output.)[17] Finally, when both conservation and production externalities coexist, conservation output decreases relative to the case in which only conservation externalities are present; as depicted in Figure 4b, where $q_i^{C_1^*}$ decreases to $q_i^{C_2^*}$.

**Comparison.** Since $C_i^K\left(0, q_{-i}^J, \theta_i^K\right) = 0$ for all $q_{-i}^J$ and $\theta_i^K$, $MC_i^C$ and $VMC_i^C$ have the same intercept, and so do $MEC_i$ and $VEC_i$. As a consequence, the leftward shift in output under incomplete information is larger than that under complete information. Hence, the presence of externalities yields more output inefficiencies when the regulator operates under incomplete than complete information.

**Selection criteria.** Our above discussion describes the optimal conservation output of Proposition 1, and how it is affected by conservation and production externalities. We were, however, silent on the conservation efficiency cutoff, $\tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$, that the procurer uses to determine whether or not it is socially optimal to have landowner $i$ enrolling in the program. Intuitively,

[17] Similarly as in the case of conservation externalities analyzed above, the $VMC_i^{C\prime}$ curve is steeper than the $VMC_i^C$ curve since they both originate at zero when $q_i^C = 0$. In words, negative production externalities from others emphasize the convexity of landowner $i$'s virtual conservation cost function.

when his conservation efficiency is relatively high, that is, $\theta_i^C \geq \tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$, he produces the conservation output $q_i^{C*}$ that solves (10) and stops the production of the market good. If, instead, his conservation efficiency is relatively low, $\theta_i^C < \tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$, he produces the market good $q_i^{M*}$, but does not generate any conservation output.[18] In particular, cutoff $\tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$ is the conservation efficiency for which landowner $i$ yields a positive welfare contribution, $\tilde{W}_i^D(q) \geq 0$, defined as follows[19]

$$\begin{aligned}\tilde{W}_i^D(q) =& V\left(q_i^C\right) - (1+\lambda)\, t_i^C\left(q_i^C\right) \\ &+ (1+\lambda)\sum_{j\neq i}\frac{\beta_j}{\beta_i}\left[\tilde{C}_j^M\left(\hat{q}_j^M, \left(q_i^C, q_k^C\right), \theta_j^M\right) - \tilde{C}_j^M\left(\hat{q}_j^{M\prime}, \left(0, q_k^{C\prime}\right), \theta_j^M\right)\right] \\ &+ (1+\lambda)\sum_{j\neq i}\frac{\beta_j}{\beta_i}\left[\tilde{C}_j^C\left(q_j^{C\prime}, \left(\hat{q}_i^M, q_k^{M\prime}\right), \theta_j^C\right) - \tilde{C}_j^C\left(q_j^C, \left(0, q_k^M\right), \theta_j^C\right)\right]\end{aligned}$$

This function considers landowner $i$'s welfare in (3) and also his weighted sum of externalities on other landowners, where $q_j^{K\prime}$ represents the output in activity $K$ of landowner $j$ without $i$'s participation. The bracket in the second line represents landowner $i$'s marginal external effect on others' virtual contingent production costs, which is positive (negative) if his total weighted externalities are negative (positive) because the procurer needs to compensate them for a lower (higher) forgone market profit. Similarly, the bracket in the third line represents the effect of landowner $i$'s market production on others' conservation costs, which is positive (negative) if his externalities are negative (positive).

**Example 3.** Consider the cost function in Examples 1 and 2, and assume that $\theta_i^K \sim U[0,1]$ for every $i$ and $K$, thus yielding

$$VMC_i^C = \frac{2\left(q_i^C + \alpha^M q_j^M\right)}{\left(1+\theta_i^C\right)^2} \quad \text{and} \quad VEC_i = -\frac{\left(\alpha^C\right)^2 q_i^C}{2\left(1+\theta_j^M\right)^2}$$

Inserting them in expression (10), yields an output level of

$$q_i^{C*} = \frac{2\left(1+\theta_j^M\right)^2\left[\alpha^M(1+\lambda)\left(1+\theta_j^M\right)p - \left(1+\theta_i^C\right)^2\right]}{(1+\lambda)\left[2\alpha^M\alpha^C\left(1+\theta_j^M\right)^2 - 8\left(1+\theta_j^M\right)^2 - \left(\alpha^C\right)^2\left(1+\theta_i^C\right)^2\right]}$$

As $q_i^{C**}$ under complete information, $q_i^{C*}$ is lower when externalities are present than absent. □

[18] The expression of landowner $i$'s cutoff $\tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$ is a function of other landowners' conservation efficiencies, $\theta_{-i}^C$, thus yielding a system of $N$ equations. Simultaneously solving for $\theta_i^C$ for every landowner $i \in N$, we obtain $\tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^M\right)$, which is no longer a function of other landowners' conservation efficiencies.

[19] This welfare contribution function is analogous to the score function in Che (1993).

### 4.2 Layers of uncertainty

Previous sections consider that the procurer can either observe the profile of pair types, $\theta = (\theta^C, \theta^M)$, in the complete information setting; or that he cannot observe the profile of $\theta^C$ nor $\theta^M$. We next analyze optimal output choices when the procurer observes landowners' market efficiency alone, i.e., $\theta^M$ but not $\theta^C$, or their conservation efficiency alone, i.e., $\theta^C$ but not $\theta^M$.

**Corollary 2.** *When the procurer only observes $\theta^M$ ($\theta^C$) he chooses the conservation output $q_i^{C*}$ that solves, respectively,*

$$MB_i^C = (1+\lambda)\left[VMC_i^C - MEC_i\right] \quad \text{and} \tag{11}$$

$$MB_i^C = (1+\lambda)\left[MC_i^C - VEC_i\right] \tag{12}$$

*respectively, if $\theta_i^C \geq \tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$. Otherwise, conservation output becomes $q_i^{C*} = 0$.*

Hence, when the procurer only observes market efficiency $\theta^M$, he does not need to consider bidder $i$'s virtual external cost since the procurer can anticipate how landowner $j$'s observed cost will be affected by landowner $i$'s conservation output. However, the procurer needs to consider the virtual marginal cost of conservation, as he does not observe landowner $i$'s conservation efficiency. A similar argument applies to the case in which the procurer observes conservation efficiency $\theta^C$ alone, whereby he uses the marginal cost of conservation but the virtual external cost, since he ignores how landowner $j$'s cost, and thus how it will be affected by a marginal increase in landowner $i$'s conservation output.

We can now compare expressions that identify optimal output levels in each information context. Starting from the setting in which the procurer observes both $\theta^M$ and $\theta^C$, i.e., $MB_i^C = (1+\lambda)\left[MC_i^C - MEC_i\right]$ in expression (5), we see that its associated output is larger than that arising in contexts in which the procurer only observes one efficiency (either $\theta^M$, as in expression 11, or $\theta^C$ as in expression 12), and also larger than in the model in which the procurer observes neither $\theta^M$ nor $\theta^C$ (see expression 10). In particular, since $VMC_i^C$ lies above $MC_i^C$, then $VMC_i^C - MEC_i > MC_i^C - MEC_i$, i.e., the right-hand side of (11) is larger than that of (5). Since $MB_i^C$ is weakly decreasing, the output that solves (11) is smaller than that of (5); as depicted in figure 5a. A similar argument applies to the comparison between expressions (12) and (5), whereby in this case $VEC_i$ lies below $MEC_i$, entailing that $MC_i^C - VEC_i > MC_i^C - MEC_i$, thus producing a lower optimal output when the procurer can only observe $\theta^C$ than in complete information; as illustrated in figure 5b.[20]

[20] The above two arguments, hence, reinforce each other when we compare optimal output in expression (5) against that in (10), as described in the previous section. This output reduction also holds when we compare the setting in which the procurer only observes $\theta^M$ against that in which he does not observe $\theta^M$ or $\theta^C$, yielding a lower optimal output as the procurer does not have further information about the landowners' efficiency.

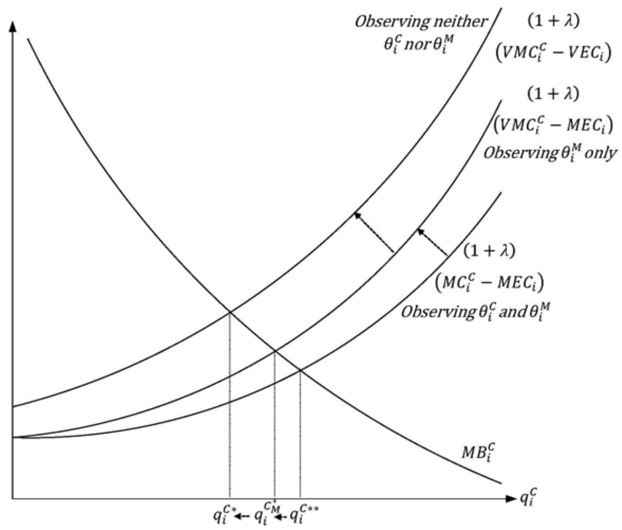


Fig 5a. Only $\theta^M$ is observed.

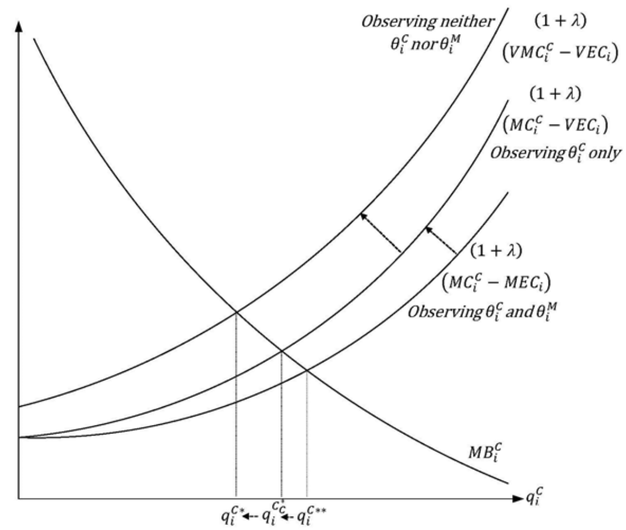


Fig 5b. Only $\theta^C$ is observed.

### 4.3 Optimal transfer profile

We next study the procurer's optimal transfer.

**Proposition 2.** *The optimal transfer for bidder $i$ is*

$$t_i^C(q_i^{C*}) = \tilde{C}_i^C\left(q_i^{C*}, q_{-i}^{M*}, \theta_i^C\right) + \left[p\hat{q}_i^M - \tilde{C}_i^M\left(\hat{q}_i^M, q_{-i}^{C*}, \theta_i^M\right)\right] \tag{13}$$

*if $\theta_i^C \geq \tilde{\theta}_i^C\left(\theta_i^M, \theta_{-i}^C, \theta_{-i}^M\right)$, and zero otherwise.*

The optimal transfer, $t_i^C(q_i^C)$, is thus zero for those who continue the market activity; but for those participating in the conservation program, it depends on the virtual conservation cost, $\tilde{C}_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)$, and the virtual contingent market profit, $p\hat{q}_i^M - \tilde{C}_i^M\left(\hat{q}_i^M, q_{-i}^C, \theta_i^M\right)$. In addition, an increase (decrease) in landowner $i$'s optimal conservation output increases (decreases) the transfer, since

$$\frac{\partial t_i^C}{\partial q_i^C} = \frac{\partial \tilde{C}_i^C\left(q_i^{C*}, q_{-i}^{M*}, \theta_i^C\right)}{\partial q_i^C} = \frac{\partial C_i^C(\cdot)}{\partial q_i^C} - \frac{1 - F_i^C\left(\theta_i^C\right)}{f_i^C\left(\theta_i^C\right)} \frac{\partial^2 C_i^C(\cdot)}{\partial \theta_i^C \partial q_i^C} > 0$$

given that marginal costs are positive and the single-crossing property holds. That is, for bidder $i$ to increase his conservation output, he needs to be compensated for the additional cost and information rent, both of them embodied in the virtual conservation cost.

Let us summarize the above results as follows: (1) without externalities, landowner $i$ receives $\tilde{C}_i^C(q_i^{C_0}, \theta_i^C) + \left[p\widehat{q}_i^M - \tilde{C}_i^M(\widehat{q}_i^M, \theta_i^M)\right]$; (2) when negative conservation externalities exist, his transfer becomes $\tilde{C}_i^C(q_i^{C_1}, \theta_i^C) + \left[p\widehat{q}_i^M - \tilde{C}_i^M(\widehat{q}_i^M, q_{-i}^{C_1}, \theta_i^M)\right]$ which is lower than that without conservation externalities since contingent market profit decreases due to others' externalities on him and his virtual conservation cost is also reduced due to a lower conservation output; and (3) when negative (positive) production externalities are also considered, his transfer becomes $\tilde{C}_i^C(q_i^{C_2}, q_{-i}^{M*}, \theta_i^C) + \left[p\widehat{q}_i^M - \tilde{C}_i^M(\widehat{q}_i^M, q_{-i}^{C_2}, \theta_i^M)\right]$, which is lower than that without production externalities because of a smaller conservation output of landowner $i$, as discussed in the previous section, which ultimately reduces (increases) his conservation cost.

# 5 Discussion

*Efficiencies with/without externalities.* Our results show that, in the absence of externalities, the procurer implements a lower output level under incomplete than complete information, as he needs to induce landowners to truthfully reveal their efficiency in the conservation program. In the presence of externalities, such output inefficiency (relative to complete information) is emphasized, as the procurer not only needs to induce landowners to reveal their efficiency in conservation, but also to compensate them for the cost increase they suffer due to externalities if they were to continue their market activities. In summary, the procurer's lack of information yields more severe inefficiencies when conservation programs generate externalities than when they do not. Alternatively, regulators would have larger efficiency gains by obtaining information about landowners' and firms' efficiency before conducting a procurement auction if, in particular, external effects emerge from conservation and/or market production.

*Ignoring the presence of externalities.* Consider a procurer who mistakenly assumes that a conservation program does not generate externalities on bidders dedicated to market activities, nor that production output entails externalities on those landowners in the conservation program. The optimal conservation output he implements would be inefficiently high (low), if either one or both types of negative (positive) externalities exist. The only setting in which his policy recommendation could be accurate would be that in which conservation output produces a negative (positive) externality while market production generates a positive (negative) externality, and their magnitudes coincide. A similar argument applies to settings where two types of externalities coexist, but regulators only consider one type (e.g., a negative externality from conservation to market activities) when designing optimal conservation outputs. In this case, the regulator would implement an excessive (insufficient) conservation output when the externality he ignores is negative (positive, respectively). Hence, the conservation program would be too aggressive as it hurts market activities, or too passive as it jeopardizes biodiversity.

*Indirect Revelation Mechanism.* In an Indirect Revelation Mechanism (IRM), the procurer can ask landowners to submit a bi-dimensional bid comprising (1) the conservation output they intend to produce; and (2) the transfer; from which the procurer can infer the underlying efficiency pairs of the landowners. The IRM would yield different output-transfer pairs than the DRM if the procurer implemented the output-transfer pair submitted by every landowner. However, the procurer does not have an incentive to implement these pairs due to the existence of externalities, which he internalizes while the landowners ignore. As a consequence, as Branco (1997) noted, the procurer can "adjust" the output-transfer pairs by proposing a take-it-or-leave-it offer to the landowners in the last stage of the IRM, which still preserves ex-ante incentive compatibility. Therefore, the DRM and IRM (after allowing for last-stage "adjustments" by the procurer as described above) produce the same outcome, that is, the same output-transfer pair $\left(q_i^C, t_i^C\right)$ for each landowner $i$.

*Further research.* Our analysis considered that firms produce a homogeneous market good sold at a given price $p$. However, a more general model could allow for a strictly decreasing demand function. In such context, market profits could be larger than in our analysis, thus implying that landowners would require a larger compensation from the procurer to dedicate their land to conservation. An alternative venue could consider that the regulator designs environmental policy to market activities simultaneously with the auction of conservation output in order to reduce the transfers necessary for voluntary participation in the auction.

# 6 Appendix

## 6.1 *Proof of Lemma 1*

Differentiating (1) with respect to $q_i^M$, landowner $i$'s optimal market output, $q_i^{M*}$, satisfies

$$\frac{\partial u_i^M\left(q_i^{M*}, \theta_i^M\right)}{\partial q_i^M} = p - \frac{\partial C_i^M\left(q_i^{M*}, q_{-i}^C, \theta_i^M\right)}{\partial q_i^M} = 0 \tag{A1}$$

such that landowner $i$ equates the expected marginal cost of production with the market price, that is, $p = \frac{\partial C_i^M\left(q_i^{M*}, q_{-i}^C, \theta_i^M\right)}{\partial q_i^M}$. While we allow externalities from conservation to production, we do not allow externalities among landowners who are still dedicated to market activities.

Differentiating A1 with respect to $\theta_i^M$, and using the Implicit Function Theorem,

$$\frac{\partial q_i^{M*}}{\partial \theta_i^M} = -\frac{\frac{\partial^2 C_i^M(q_i^{M*}, q_{-i}^C, \theta_i^M)}{\partial q_i^M \partial \theta_i^M}}{\frac{\partial^2 C_i^M(q_i^{M*}, q_{-i}^C, \theta_i^M)}{\partial (q_i^M)^2}} \geq 0$$

Totally differentiating A1 with respect to $\theta_i^M$, and using the Envelope Theorem,

$$\frac{du_i^M\left(q_i^{M*}, \theta_i^M\right)}{d\theta_i^M} = \underbrace{\frac{\partial u_i^M\left(q_i^{M*}, \theta_i^M\right)}{\partial q_i^M}}_{=0 \text{ by Envelope Theorem}} \underbrace{\frac{\partial q_i^{M*}}{\partial \theta_i^M}}_{\geq 0} - \underbrace{\frac{\partial C_i^M\left(q_i^M, q_{-i}^C, \theta_i^M\right)}{\partial \theta_i^M}}_{\leq 0 \text{ by Assumption 1}} \geq 0$$

## 6.2 *Proof of Lemma 2*

When the procurer observes $\theta_i^C$ and $\theta_i^M$, he solves the following welfare maximization program.

$$\begin{aligned}
&\max_{q^C,t^C} W\left(q^C,t^C\right) \\
&= \max_{\{q_i^C(\cdot),t_i^C(\cdot)\}} \sum_{i=1}^{N} \beta_i \left[V\left(q_i^C\right) - (1+\lambda)\, t_i^C\left(q_i^C\right)\right] \quad \text{by (3)} \\
&= \max_{\{q_i^C(\cdot)\}} \sum_{i=1}^{N} \beta_i \left\{V\left(q_i^C\right) - (1+\lambda)\left[u_i^C\left(q_i^C,\theta_i^C\right) + C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right)\right]\right\} \quad \text{by (1)}
\end{aligned}$$

The Individual Rationality constraint must be binding, otherwise the procurer could reduce the residual utility and still induce the participation of landowner $i$. We thus obtain

$$u_i^C\left(q_i^C,\theta_i^C\right) = u_i^M\left(q_i^M,\theta_i^M\right) = pq_i^M - C_i^M\left(q_i^M, q_{-i}^C, \theta_i^M\right)$$

such that we can rewrite the procurer's welfare maximization program as follows:

$$\max_{\{q_i^C(\cdot)\}} \sum_{i=1}^{N} \beta_i \left\{V\left(q_i^C\right) - (1+\lambda)\left[C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right) + pq_i^M - C_i^M\left(q_i^M, q_{-i}^C, \theta_i^M\right)\right]\right\}$$

Differentiating with respect to $q_i^C$, the optimal conservation output, $q_i^{C**}$, satisfies

$$\underbrace{\frac{\partial V(q_i^{C**})}{\partial q_i^C}}_{MB_i^C} = (1+\lambda)\left[\underbrace{\frac{\partial C_i^C(q_i^{C**}, q_{-i}^{M**}, \theta_i^C)}{\partial q_i^C}}_{MC_i^C} - \underbrace{\sum_{j\neq i} \frac{\beta_j}{\beta_i} \frac{\partial C_j^M(\hat{q}_j^M, q_{-j}^{C**}, \theta_j^M)}{\partial q_i^C}}_{MEC_i}\right]$$

where $\hat{q}_j^M$ denotes landowner $j$'s contingent market output. And from the condensed welfare maximization program above, we can infer that procurer's transfer function to landowner $i$, $t_i^C\left(q_i^C\right)$, under complete information is

$$t_i^C\left(q_i^C\right) = C_i^C\left(q_i^C, q_{-i}^M, \theta_i^C\right) + \left[p\hat{q}_i^M - C_i^M\left(\hat{q}_i^M, q_{-i}^C, \theta_i^M\right)\right]$$

### 6.3 *Proof of Proposition 1*

When the procurer observes neither $\theta_i^C$ nor $\theta_i^M$, he solves the following welfare maximization program.

$$\begin{aligned}
&\max_{q^C,t^C} E_\theta\left[W\left(q^C,t^C\right)\right]\\
&=\max_{\{q_i^C(\cdot),t_i^C(\cdot)\}} E_\theta\sum_{i=1}^{N}\beta_i\left[V\left(q_i^C\right)-(1+\lambda)\,t_i^C\left(q_i^C\right)\right] \quad \text{by (3)}\\
&=\max_{\{q_i^C(\cdot)\}} E_\theta\sum_{i=1}^{N}\beta_i\left\{V\left(q_i^C\right)-(1+\lambda)\left[u_i^C\left(q_i^C,\theta_i^C\right)+C_i^C\left(q_i^C,q_{-i}^M,\theta_i^C\right)\right]\right\} \quad \text{by (1)}
\end{aligned}$$

The Individual Rationality constraint (8) must be binding, otherwise the procurer could reduce the residual utility and still induce the participation of landowner $i$. We thus obtain

$$u_i^C(\underline{q}_i^C,\underline{\theta}_i^C)=u_i^M(\overline{q}_i^M,\overline{\theta}_i^M)$$

where $\underline{q}_i^C\equiv q_i^C\left(\underline{\theta}_i^C\right)$ and $\overline{q}_i^M\equiv q_i^C\left(\overline{\theta}_i^M\right)$. Applying Myerson's Characterization Theorem (Myerson, 1981) to the Bayesian Incentive Compatibility constraints (6) and (7) and substituting into the above expression, yields

$$\begin{aligned}
u_i^C(q_i^C,\theta_i^C)=&pq_i^M-E_{q_{-i}^C}\left[C_i^M\left(q_i^M,q_{-i}^C,\theta_i^M\right)\right]-\int_{\theta_i^M}^{\overline{\theta}_i^M}E_{q_{-i}^C}\left[\frac{\partial C_i^M(q_i^M,q_{-i}^C,\breve{\theta}_i^M)}{\partial\theta_i^M}\right]d\breve{\theta}_i^M\\
&-\int_{\underline{\theta}_i^C}^{\theta_i^C}E_{q_{-i}^M}\left[\frac{\partial C_i^C(q_i^C,q_{-i}^M,\breve{\theta}_i^C)}{\partial\theta_i^C}\right]d\breve{\theta}_i^C
\end{aligned}$$

such that by applying the Law of Iterated Expectation because the procurer takes expectation directly of how landowners take expectation of the conservation-production efficiency parameters of each other, we can rewrite the procurer's welfare maximization program as follows:

$$\max_{\{q_i^C(\cdot)\}} E_\theta\sum_{i=1}^{N}\beta_i\left\{V\left(q_i^C\right)-(1+\lambda)\left[\begin{array}{c} C_i^C\left(q_i^C,q_{-i}^M,\theta_i^C\right)-\displaystyle\int_{\underline{\theta}_i^C}^{\theta_i^C}\frac{\partial C_i^C\left(q_i^C,q_{-i}^M,\breve{\theta}_i^C\right)}{\partial\theta_i^C}d\breve{\theta}_i^C\\ +pq_i^M-C_i^M\left(q_i^M,q_{-i}^C,\theta_i^M\right)-\displaystyle\int_{\theta_i^M}^{\overline{\theta}_i^M}\frac{\partial C_i^M(q_i^M,q_{-i}^C,\breve{\theta}_i^M)}{\partial\theta_i^M}d\breve{\theta}_i^M\end{array}\right]\right\}$$

Using integration by parts, the procurer's social welfare function becomes

$$\max_{\{q_i^C(\cdot)\}} E_\theta\sum_{i=1}^{N}\beta_i\left\{V(q_i^C)-(1+\lambda)\left[\tilde{C}_i^C(q_i^C,q_{-i}^M,\theta_i^C)+pq_i^M-\tilde{C}_i^M(q_i^M,q_{-i}^C,\theta_i^M)\right]\right\} \tag{A2}$$

Differentiating A2 with respect to $q_i^C$, the optimal conservation output, $q_i^{C*}$, satisfies

$$\underbrace{\frac{\partial V(q_i^{C*})}{\partial q_i^C}}_{MB_i^C} = (1+\lambda)\left[\underbrace{\frac{\partial \tilde{C}_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial q_i^C}}_{VMC_i^C} - \underbrace{\sum_{j\neq i}\frac{\beta_j}{\beta_i}\frac{\partial \tilde{C}_j^M(\hat{q}_j^M, q_{-j}^{C*}, \theta_j^M)}{\partial q_i^C}}_{VEC_i}\right] \tag{A3}$$

In addition,

$$\begin{aligned}\frac{\partial^2 W(q^*)}{\partial (q_i^C)^2} =& \frac{\partial^2 V(q_i^{C*})}{\partial (q_i^C)^2} - (1+\lambda)\left[\frac{\partial^2 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial (q_i^C)^2} - \frac{1-F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)}\frac{\partial^3 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial (q_i^C)^2\partial\theta_i^C}\right] \\ &+ (1+\lambda)\sum_{j\neq i}\frac{\beta_j}{\beta_i}\left[\frac{\partial^2 C_j^M(\hat{q}_j^M, q_{-j}^{C*}, \theta_j^M)}{\partial (q_i^C)^2} + \frac{F_j^M(\theta_j^M)}{f_j^M(\theta_j^M)}\frac{\partial^3 C_j^M(\hat{q}_j^M, q_{-j}^{C*}, \theta_j^M)}{\partial (q_i^C)^2\partial\theta_j^M}\right]\end{aligned}$$

By assumption 1, the second term in the first bracket is negative such that the first bracket is positive. Then, by assumption 3, the second bracket is positive if the (second-order) direct external effect that landowner $i$'s positive externality dampens the curvature of landowner $j$'s production cost curve, $\frac{\partial^2 C_j^M(\hat{q}_j^M, q_{-j}^{C*}, \theta_j^M)}{\partial (q_i^C)^2} \geq 0$, more than offsets the (third-order) indirect attenuation effect that landowner $j$'s production efficiency weakens the positive external effect from landowner $i$, $\frac{F_j^M(\theta_j^M)}{f_j^M(\theta_j^M)}\frac{\partial^2 C_j^M(\hat{q}_j^M, q_{-j}^{C*}, \theta_j^M)}{\partial (q_i^C)^2\partial\theta_j^M} \leq 0$.

Differentiating (A3) with respect to $\theta_i^C$,

$$\begin{aligned}\frac{\partial q_i^{C*}}{\partial \theta_i^C} =& (1+\lambda)\left[\frac{\partial^2 W(q^*)}{\partial (q_i^C)^2}\right]^{-1} \\ &\left\{\left[1 - \frac{\partial}{\partial\theta_i^C}\left(\frac{1-F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)}\right)\right]\frac{\partial^2 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial q_i^C\partial\theta_i^C} - \frac{\partial^3 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial q_i^C\partial(\theta_i^C)^2}\right\}\end{aligned}$$

As the cumulative density function $F_i^C(\theta_i^C)$ weakly increases in $\theta_i^C$, the inverse hazard rate $\frac{1-F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)}$ weakly decreases in $\theta_i^C$ such that $\left[1 - \frac{\partial}{\partial\theta_i^C}\left(\frac{1-F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)}\right)\right] > 0$. In addition, by assumption 1, we can determine that: (1) $\frac{\partial^2 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial q_i^C\partial\theta_i^C} \leq 0$, i.e., single crossing condition; and (2) $\frac{\partial^3 C_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial q_i^C\partial(\theta_i^C)^2} = \frac{\partial^3 MC_i^C(q_i^{C*}, q_{-i}^{M*}, \theta_i^C)}{\partial(\theta_i^C)^2} \geq 0$. Finally, by the concavity of the welfare function, $\frac{\partial^2 W(q^*)}{\partial (q_i^C)^2} \leq 0$, which helps us to ultimately determine that optimal conservation output $q_i^{C*}$ is monotonically increasing in conservation efficiency $\theta_i^C$.

We next derive the contribution function of landowner $i$ to social welfare, denoting $G_i$ to be the welfare gain from producing conservation output, $q_i^C$, and $L_i$ to be the welfare loss from stopping the production of the market good, $q_i^M$, respectively. First, conducting an anti-derivative of (A3) with respect to $q_i^C$,

$$\begin{aligned}
G_i(q_i^C) =& G_i(\underline{q}_i^C) + \int_{\underline{q}_i^C}^{q_i^C} \frac{\partial V(\breve{q}_i^C)}{\partial q_i^C} d\breve{q}_i^C \\
&- (1+\lambda) \int_{\underline{q}_i^C}^{q_i^C} \left( \frac{\partial \tilde{C}_i^C(\breve{q}_i^C, q_{-i}^M, \theta_i^C)}{\partial q_i^C} - \sum_{j\neq i} \frac{\beta_j}{\beta_i} \frac{\partial \tilde{C}_j^M(\hat{q}_j^M, (\breve{q}_i^C, q_k^C), \theta_j^M)}{\partial q_i^C} \right) d\breve{q}_i^C \\
=& G_i(\underline{q}_i^C) + V(q_i^C) - V(\underline{q}_i^C) - (1+\lambda) \left[ \tilde{C}_i^C(q_i^C, q_{-i}^M, \theta_i^C) - \tilde{C}_i^C(\underline{q}_i^C, q_{-i}^M, \theta_i^C) \right] \\
&+ (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^M(\hat{q}_j^M, (q_i^C, q_k^C), \theta_j^M) - \tilde{C}_j^M(\hat{q}_j^{M\prime\prime}, (\underline{q}_i^C, q_k^C), \theta_j^M) \right]
\end{aligned}$$

where $q_j^{M\prime\prime}$ represents the *contingent* market output of landowner $j \neq i$ under the externality imposed by landowner $i$ being the least efficient in conservation, alongside other landowners $k \neq \{i, j\}$. Second, evaluating welfare gain generated by the type $\underline{\theta}_i^C$ landowner $i$,

$$\begin{aligned}
G_i(\underline{q}_i^C) =& V(\underline{q}_i^C) - (1+\lambda) \left[ \tilde{C}_i^C(\underline{q}_i^C, q_{-i}^M, \theta_i^C) + p\hat{q}_i^M - \tilde{C}_i^M(\hat{q}_i^M, q_{-i}^C, \theta_i^M) \right] \\
&+ (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^M(\hat{q}_j^{M\prime\prime}, (\underline{q}_i^C, q_k^C), \theta_j^M) - \tilde{C}_j^M(\hat{q}_j^{M\prime}, (0, q_k^{C\prime}), \theta_j^M) \right]
\end{aligned}$$

where $q_j^{K\prime}$ is the output of landowner $j \neq i$ in activity $K$ without landowner $i$'s participation. Third, combining the above results, welfare gain of type $\theta_i^C$ landowner $i$ is

$$\begin{aligned}
G_i(q_i^C) =& V(q_i^C) - (1+\lambda) \left[ \tilde{C}_i^C(q_i^C, q_{-i}^M, \theta_i^C) + p\hat{q}_i^M - \tilde{C}_i^M(\hat{q}_i^M, q_{-i}^C, \theta_i^M) \right] \\
&+ (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^M(\hat{q}_j^M, (q_i^C, q_k^C), \theta_j^M) - \tilde{C}_j^M(\hat{q}_j^{M\prime}, (0, q_k^{C\prime}), \theta_j^M) \right]
\end{aligned}$$

Fourth, welfare loss is characterized by the removal of production externality on other landowners, as landowner $i$ no longer produces the market good, such that

$$L_i(q_i^M) = (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^C(q_j^{C\prime}, (q_i^M, q_k^{M\prime}), \theta_j^C) - \tilde{C}_j^C(q_j^C, (0, q_k^M), \theta_j^C) \right]$$

Fifth, his contribution to social welfare is found by taking welfare loss $L_i$ off welfare gain $G_i$,

$$\begin{aligned}
\tilde{W}_i^D(q) =& G_i(q_i^C) + L_i(q_i^M) \\
=& V(q_i^C) - (1+\lambda) \left[ \tilde{C}_i^C(q_i^C, q_{-i}^M, \theta_i^C) + p\hat{q}_i^M - \tilde{C}_i^M(\hat{q}_i^M, q_{-i}^C, \theta_i^M) \right] \\
&+ (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^M(\hat{q}_j^M, (q_i^C, q_k^C), \theta_j^M) - \tilde{C}_j^M(\hat{q}_j^{M\prime}, (0, q_k^{C\prime}), \theta_j^M) \right] \\
&+ (1+\lambda) \sum_{j\neq i} \frac{\beta_j}{\beta_i} \left[ \tilde{C}_j^C(q_j^{C\prime}, (\hat{q}_i^M, q_k^{M\prime}), \theta_j^C) - \tilde{C}_j^C(q_j^C, (0, q_k^M), \theta_j^C) \right]
\end{aligned}$$

Finally, we verify that $\tilde{W}_i^D(q)$ is monotonically increasing in $\theta_i^C$,

$$\frac{\partial \tilde{W}_i^D(q)}{\partial \theta_i^C} = \left\{ \frac{\partial V(q_i^C)}{\partial q_i^C} - (1+\lambda)\left[ \frac{\partial \tilde{C}_i^C(q_i^C, q_{-i}^M, \theta_i^C)}{\partial q_i^C} - \sum_{j \neq i} \frac{\beta_j}{\beta_i} \frac{\partial \tilde{C}_j^M(\hat{q}_j^M, q_{-j}^C, \theta_j^M)}{\partial q_i^C} \right] \right\} \frac{\partial q_i^C}{\partial \theta_i^C}$$
$$- (1+\lambda) \left\{ \left[ 1 - \frac{\partial}{\partial \theta_i^C} \left( \frac{1 - F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)} \right) \right] \frac{\partial C_i^C(q_i^C, q_{-i}^M, \theta_i^C)}{\partial \theta_i^C} - \frac{1 - F_i^C(\theta_i^C)}{f_i^C(\theta_i^C)} \frac{\partial^2 C_i^C(q_i^C, q_{-i}^M, \theta_i^C)}{\partial (\theta_i^C)^2} \right\}$$

which, by the Envelope Theorem, the first brace is zero. Then, by assumption 1, the whole term under the second brace is negative such that $\frac{\partial \tilde{W}_i^D(q)}{\partial \theta_i^C} \geq 0$ and $\tilde{W}_i^D(q)$ is monotonically increasing in $\theta_i^C$. ■

### 6.4 *Proof of Corollary 2*

When the procurer observes the profile of $\theta^M$, but not that of $\theta^C$, he only treats the observed profile $\theta^M$ as a parameter. Following an approach similar to Myerson (1981), it is straightforward to obtain expression (11). An analogous argument applies in the case that the procurer observes the profile of $\theta^C$, but not that of $\theta^M$, obtaining expression (12). ■

### 6.5 *Proof of Proposition 2*

Equating equation (4) with (A2), the procurer's transfer function to landowner $i$, $t_i^C(q_i^C)$, is

$$t_i^C(q_i^C) = \tilde{C}_i^C(q_i^C, q_{-i}^M, \theta_i^C) + p\hat{q}_i^M - \tilde{C}_i^M(\hat{q}_i^M, q_{-i}^C, \theta_i^M)$$

which is different from the welfare gain function, $G_i(q_i^C)$, from above and landowner $i$ does not compensate (or is not compensated) for the positive (negative) conservation externality on others because this is already included in the transfer function the procurer proposes to other landowners $j \neq i$. ■

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