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Department of Food and Resource Economics (IFRO)
University of Copenhagen
Rolighedsvej 25
DK 1958 Frederiksberg DENMARK
www.ifro.ku.dk/english/

A Montero auction mechanism for regulating unobserved use of the commons*

Lars Gårn Hansen

University of Copenhagen, Institute of Food and Resource Economics, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark

Tel: +45 35 33 68 33. E-mail address:lgh@ifro.ku.dk.

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ABSTRACT:

Regulating externalities from the use of common resources is often hampered by the regulator's inability to accurately observe individual firms' resource use. Allocating resource use through taxes on *aggregate* use, which often can be observed, has been suggested (Segerson, 1988); however, these taxes are vulnerable to collusion and strategic behavior and they generate inefficient entry-exit incentives. To address these disadvantages, I suggest using a Montero (2008)-type auction mechanism to allocate licenses for unobserved use of common resources and to induce compliance with these licenses through an enforcement tax on the differences between *aggregated* licenses issued and observed *aggregated* resource use.

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Key words: incentive mechanisms; unobservable resource use; non-point emissions; Truthful revelation

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1. Introduction

Regulating externalities from the use of common resources such as air, water, and valuable ecosystems is an important economic problem. It is common to base such regulations on pollution licenses or resource extraction quotas and recently Montero (2008) has proposed an auction mechanism that implements the truthful revelation of demand schedules for such licenses in dominant strategies. This is achieved by refunding a certain proportion of the auction revenue to resource users. This auction scheme essentially implements the truthful revelation mechanism proposed by Dasgupta, Hammond, and Maskin (1980) through policy instruments (auction and refund of a proportion of the auction revenue) that are normally used in practice. Montero (2008) assumes that firms comply with the licenses purchased. This is a reasonable assumption when each individual firm's resource use can be observed by the regulator because then it is easy for the regulator to detect and punish non-compliance. However, when the firms' individual resource use cannot be observed, the regulator cannot detect non-compliance with licenses, and firms have no incentive to purchase or comply with licenses for resource use.

When firms' resource use cannot be observed, regulation is often based on the observable use of inputs or capital; however, this may be inefficient (Xepapadeas, 2011). As an alternative, economists have suggested incentives based on (a measure of) *aggregate* common resource use (e.g., Segerson 1988, Cabe & Herriges, 1992, Xepapadeas, 1992, Hansen, 1998, Horan et al., 1998, and Hansen and Romstad, 2007). Although firm level measurement is infeasible, aggregated measures can often be derived from, e.g., changes in resource stocks or ambient pollution levels that the regulator can observe. The idea is to impose a tax based on the measured aggregate of all firms' resource use. This can provide efficient incentives because the aggregate use and thereby the tax paid by an individual resource user increases when he increases his own utilization. However, these mechanisms have important disadvantages. The first disadvantage is that the aggregate tax base generally makes collusion among firms profitable and, if collusion is successful, it can distort incentives. This is recognized in all the cited papers and has been shown experimentally by, e.g., Suter et al (2008). The second generally recognized disadvantage is that entry and exit incentives are inefficient. Finally, implementation of the optimal equilibrium under these mechanisms requires iterations in which tax incentives and firms' resource use are adjusted over several periods until equilibrium is attained. This implies a risk of strategic behavior, which may distort incentives (as noted by, e.g., Karp (2005) and shown experimentally by, e.g., Vossler et al, 2013). Avoiding these disadvantages requires the regulator to know firms' private cost information, which these mechanisms do not induce firms to reveal.

This is the point of departure for this paper. I suggest combining a Montero auction mechanism for allocating licenses for use of the commons with a tax on *unlicensed aggregate* commons use. The idea is that a tax on unlicensed aggregate use of a common resource will induce compliance with the licenses that are allocated through a Montero auction mechanism. This implements the optimum allocation if individual firms are able to coordinate on the Nash equilibrium in which all firms comply with the allocated licenses. Conditional on this compliance equilibrium, truthful revelation of private cost information is ensured which makes the proposed scheme efficient, collusion proof and ensures that it provides correct entry-exit incentives. The compliance equilibrium is easily identified by firms because it is the sole focal equilibrium. This equilibrium is also likely to be perceived as resulting in a fair distribution of tax payments and, therefore, to be viewed as an attractive state in which to coordinate. In addition, the likelihood of coordination on this state can be increased by facilitating communication between resource users without endangering the efficiency of the resulting allocation. The proposed tax appears to be a potentially attractive alternative for regulation of common resource use in which aggregate use can be measured accurately but in which measurement costs make the observation of an individual firm's resource use difficult. The main weakness of the mechanism is that the compliance equilibrium is a focal Nash equilibrium and not a dominant strategy.

The mechanism I propose (potentially) extends the applicability of Montero's (2008) core contribution to regulation situations in which firm level measurement of externality generation is not feasible. The tax mechanism proposed by Hansen and Romstad (2007) is the most similar prior proposal in the literature. Hansen and Romstad (1997) combine a tax based on aggregate use with the self-reporting of individual use, which allows them to address the collusion and entry-exit problems inherent in the aggregate tax mechanism. However, the tax mechanism proposed by Hansen and Romstad does not address the strategic interaction problem nor s does it induce revelation of firms' private cost information so that the corrections they suggest are only ad hoc approximations. Finally, using a tax on aggregate behavior to induce compliance with regulations is, as far as I know, novel to the literature on compliance and enforcement building on Beacker (1968).

This paper is organized as follows. In section 2, I introduce a model and prior results. Section 3 presents the suggested tax mechanism, and in section 4, we investigate the induced firm behavior. In section 5, we investigate other properties of the proposed regulatory mechanism. Section 6 concludes this paper.

2. The model

In this section, I develop a model of an industry with negative external effects on other parts of the economy. We may, for example, imagine a group of farmers using a common water resource such as a stream for irrigation. This results in external costs by degrading a downstream ecosystem dependent on the same water supply or by reducing alternative industrial or residential water use. Accurate measurement of individual farmers' water use is excessively costly; however,, it is possible for the regulator to measure aggregate water use, for example, by comparing water flow up and downstream from the group of farms in question. Let the industry consist of *n* firms, where x_i denotes the quantity of water resources used by firm *i*, and $\pi_i(x_i)$ is firm *i*'s profit from resource use, and $D(\sum_{i=1}^{n} x_i)$ is the total external damage to other parts of the economy caused by the industries' total water resource use. The regulator observes aggregated resource use ($x = \sum_{i=1}^{n} x_i$), but not individual firms' use (x_i) nor individual firms' profit functions $\pi_i(x_i)$.[1]

I assume that the marginal damage is positive and increasing ($D' > 0$ and $D'' \geq 0$). I also assume that $\pi_i'(0) > 0$ and $\pi_i'' < 0$; this implies that, if a firm uses more, its marginal profit from pollution decreases. If a firm must pay a fixed price (*p*) for using x_i, the firm's demand curve would be $X_i(p) = \pi_i'^{-1}(p)$. Without regulation, the firm uses $x_i^0 = X_i(0)$, characterized by $\pi_i'(x_i^0) = 0$. This corresponds to a firm's demand for resource licenses when the fixed price for licenses approaches zero. The optimal total resource use and its allocation across firms is found by solving the following maximization problem:

$$\underset{x_1,\ldots x_n}{Max} \sum_{i=1}^{n} \pi_i(x_i) - D(x) \quad \text{where} \quad x = \sum_{i=1}^{n} x_i \text{ is aggregate resource use} \qquad (1)$$

The first best solution, $x_1^*,\ldots,x_n^*$, satisfies the following *n* first order conditions:

$$\pi_i'(x_i) = D'(x) \qquad \text{for } i = 1,\ldots,n \qquad (2)$$

Without regulation, a firm would generally use more than the pareto efficient amount of resources (i.e., $x_i^* \leq x_i^0$) because it would be profitable for the firm to increase resource use until marginal profit is zero.

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[1] The model could also apply to a polluting industry in which the aggregate pollution can be observed, whereas individual emissions cannot. In that case, firm *i* pollutes x_i , thereby degrading the environment, $\pi_i(.)$ is the abatement costs the firm saves when it is allowed to pollute and $D(.)$ is the total environmental damages from the industry's pollution. Another example in which the model may be applicable is fishing, in which the aggregate catch may be estimated from stock measurements, whereas individual fishermen's catch because of illegal landings or discards are difficult to observe (se Montero, 2007, for proof of the extension of his mechanism to situations where resource users inflict externalities on each other as is typically the case for fisheries)..

If the regulator knows the damage function ($D(.)$) and can observe an individual firm's use (x_i), but *does not* know the firm's profit functions ($\pi_i(.)$), the regulator must provide incentives for the firm to reveal this information. To reveal this private information, Montero (2008) proposes a uniform-price sealed-bid auction of an endogenous number of licenses combined with a payback of part of the auction revenue. Montero (2008) shows that this mechanism induces the truthful disclosure of the private information and implements the optimal solution in dominant strategies. In addition, Montero (2008) finds that the regulatory scheme is collusion-proof and that each firm's total tax payment equals the externality inflicted on other firms evaluated at the margin. These are very attractive properties; however, it is critical for the implementation of this mechanism that the regulator is able to enforce firms' compliance with the allocated licenses. It is, of course, straightforward to enforce compliance when the regulator can observe an individual firm's resource use. In this case, the regulator can detect and punish a firm that is using resources in excess of allocated licenses.

In the situation considered in this paper, the regulator cannot observe individual firms' resource use (x_i). This makes it impossible for the regulator to ensure compliance with licenses using a traditional enforcement policy; therefore, he cannot apply Montero's mechanism to allocate such licenses. If compliance is not ensured, firms have no incentive to purchase licenses because the firms can instead use the resource 'illegally' at no cost.

To get around the problem of unobservability of an individual firm's resource use, the previous literature suggests imposing taxes based on measures of *aggregate* use ($x = \sum_{i=1}^{n} x_i$), which I assume the regulator can observe. The idea in previous contributions is that because each firm's individual use influences the aggregate use, optimal individual incentives can be induced by making firms pay a tax on the aggregate. Then, each firm maximizes:

$$\underset{x_i}{Max}\, \pi_i(x_i) - tx \qquad (3)$$

where the *n* first order conditions for profit maximization are:

$$\pi_i'(x_i) = t \qquad \text{for } i = 1,...,n \qquad (4)$$

By using a constant tax rate as suggested by Segerson (1988), the regulator implements the optimum in dominant strategies. Because the regulator does not know the optimal aggregate use, x^*, the tax rate must be adjusted over time until the marginal damage evaluated at the resulting aggregate use level is equal to the tax incentive (i.e., until $t = D(x^*)$). However, if firms realize that their current resource use affects the future tax rates determined by the regulator, they may form conjectures regarding this relationship and act strategically (see Karp (2005)). If firms take conjectural variations into account when solving (3), they will no longer apply the first order condition provided by (4), and the resulting equilibrium will be inefficient[2]. In experiments established to reflect tax adjustment dynamics in this type of regulation, Vossler et al (2013) find that many subjects act strategically in this manner and that the equilibrium is substantially affected.

Furthermore, as noted in numerous prior studies,[3] the firms can increase profits by colluding to reduce resource use below the level implied by (4). This occurs because the aggregate emission tax implies that an emission reduction by one firm reduces the tax payment of all firms. In experiments using this type of tax mechanism, Suter et al (2008) find that by allowing cheap talk communication, close to perfect profit maximizing collusion can be induced, resulting in substantial effects on the resulting equilibrium; this demonstrates the vulnerability of this type of tax mechanism to collusion.

Finally, the dynamic adjustment process reveals marginal damage to the regulator, not the total, infra-marginal externality contribution of each firm (see, e.g., Horan et al, 1998). Therefore, the regulator cannot ensure that an individual firm's total tax payment

[2] The regulator could instead set the tax equal to $D(x)$, as suggested by Hansen 1998 and Horan et al (1998), such that the tax system does not change over time. This circumvents strategic interaction between the regulator and firms, but then introduces strategic interaction among firms because tax incentives depend on aggregate emissions *x*.

[3] e.g., Segerson 1988, Cabe & Herriges, 1992, Xepapadeas, 1992, Hansen, 1998, Horan et al,1998, and Hansen and Romstad, 2007.

equals the total externality generated by the firm. Thus, these mechanisms do not generally ensure efficient entry and exit incentives.

3. A Montero auction for non-point emissions

In the situation I consider, the regulator knows the damage function, *D(.)*. However, the regulator cannot measure individual firms' resource use (x_i). This is an additional complication compared to the situation studied by Montero (2008). I assume that the regulator knows which firms contribute to pollution and that aggregate resource use (*x*) can be measured accurately such that the regulator observes *x*. The regulator does not know the individual firms' profit functions, $\pi_i(.)$. However, I assume that the regulator is able to specify an upper bound, *f*, on firms' marginal profits from resource use, i.e.:

$$f \geq \underset{i}{Max}\, \pi_i'(0) \tag{5}$$

The regulator must be able to specify such an *f* if she is to implement an effective enforcement tax.

The idea of the mechanism proposed in this paper is to use a tax on aggregate resource use as an enforcement mechanism (rather than as an allocation mechanism). This ensures that firms comply with the pollution licenses that are allocated through a Montero-auction. Thus, the enforcement tax on aggregate emissions is an alternative to the standard enforcement system, which cannot ensure compliance when individual firms' resource use is unobservable. This, in turn, allows the Montero- auction to solve the problem of coordinating emissions between firms, which allocation mechanisms based on aggregate use alone cannot solve.

Specifically, I suggest the following combined Montero auction/aggregate tax mechanism:

> Initially, the regulator informs firms of the license auction scheme and the enforcement tax as specified below. Then, the regulator announces a decreasing aggregate supply schedule for pollution licenses, which is specified as the inverse of the marginal damage function:

$$S(p) = D'^{-1}(p) \qquad (6)$$

Thereafter, each individual firm must submit a non-increasing demand schedule, $L_i(p)$, for licenses to the regulator. With this information, the regulator calculates a license supply function for firm *i*, which is equal to the aggregate supply schedule minus the aggregate of demand schedules from all other firms except *i*:

$$S_i(p) = S(p) - L_{-i}(p) \text{ where } L_{-i}(p) = \sum_{j \neq i} L_j(p) \qquad (7)$$

Then, the regulator determines the license price, p^*, and license quantity, l_i^*, that clears the market (is contained in the firm's demand schedule, $L_i(p)$, as well as in the regulator's residual supply function). Then, each individual firm is refunded a fraction, $\alpha_i(l_i^*)$, of the auction revenues (i.e., the payback-function is $\alpha_i(l_i^*)p^*l_i^*$).

At the end of the time period, the regulator collects an enforcement tax. First, the regulator measures the aggregate resource use, *x*, and calculates the differences from the total auctioned license quantity ($l^* = \sum_{j=1}^{n} l_i^*$). Then, all firms pay an enforcement tax based on this difference of $f\left|x - l^*\right|$ where *f* is the tax rate set sufficiently high to ensure that (5) holds.

By construction, the same equilibrium price, p^*, clears all *n* auctions because the equilibrium condition for auction *i*, $S_i(p) = L_i(p)$ implies that:

$$S(p) = L(p) \qquad (8)$$

The consequence of this equilibrium condition is that the equilibrium price equals the marginal damage of emissions when the market clearing quantity of licenses is issued[4]:

$$p^* = D'(l^*) \qquad \text{where } l^* = \sum l_i^* = L(p^*) \tag{9}$$

Using (8), the regulator can calculate the price, p_{-i}^*, that clears the auction if firm *i* did not pollute at all. This price is the solution to $S(p) = L_{-i}(p)$. Furthermore, the regulator can derive the license demand for all the other firms as a function of the license demand of firm *i*. This is implicitly determined by the equilibrium condition $S(p) = l_i + L_{-i}(p)$ i.e.:

$$\tilde{L}_{-i}(l_i) \qquad \text{where } l_{-i}^* = \tilde{L}_{-i}(l_i^*) \text{ and } L_{-i}(p_{-i}^*) = \tilde{L}_{-i}(0) \tag{10}$$

With this, the regulator can calculate the payback-function as:

$$\alpha_i(l_i^*) = 1 - \frac{\tilde{D}_i(l_i^*)}{p^* l_i^*} \quad \text{Where } \tilde{D}_i(l_i^*) = \int_{z=0}^{l_i^*} D'(z + \tilde{L}_{-i}(z))dz \tag{11}$$

Montero calls $\tilde{D}_i(l_i^*)$ firm *i*'s residual damage function because it measures the external damage caused by firm *i* when it increases emissions from zero to l_i^* conditional on the licenses purchased by all other firms. Note that the definition of the residual damage function $\tilde{D}_i(l_i^*)$ implies that:

$$\frac{d\tilde{D}_i(l_i^*)}{dl_i^*} = D'(l^*) \tag{12}$$

[4] Applying the damage function to both sides of $S(p) = L(p)$ and using (6) gives (9)

Finally, firms pay a tax on the *difference* between the total auctioned license quantity and the measured aggregated emissions. Note that the tax payment increases if firms, as a whole, purchase *more* licenses than they need as well as if they purchase less licenses then needed. This is an enforcement tax designed to induce firms to purchase precisely the aggregate quantity of licenses that corresponds to their aggregate resource use because all deviations are penalized at the marginal tax rate *f*. Note that the specific tax rate we apply is not important as long as it is greater than the upper bound on firms' marginal profits from emissions as indicated in (5). If the regulator has minimal knowledge of the technologies applied in the industry, she may need to specify an *f* that is substantially larger than $\underset{i}{Max}\,\pi_i'(0)$ to ensure (5). However, regulators often have knowledge of the standard technologies, enabling the specification of an upper bound close to $\underset{i}{Max}\,\pi_i'(0)$.

The auction/payback element of the suggested mechanism corresponds to the auction-mechanism suggested by Montero (2008) for point source pollution problems (in which firm emissions *can* be observed). The enforcement tax on the difference between aggregate emissions and aggregate license purchases is related to the ambient tax suggested for non-point source pollution problems by Segerson (1988) and others because it is based on aggregated measures of firm behavior. However, this tax differs in that it is designed to induce aggregate compliance with licenses rather than to allocate emissions among firms.

4. Firms' behavior under the auction mechanism

The tax mechanism specifies that licenses are allocated and paid for prior to production and resource use being implemented. Therefore, the firm encounters a sequential maximization where firm *i* first must decide how many pollution licenses, l_i, to buy, and then after licenses have been allocated and paid for the firm must determine how much to pollute x_i. Formally, the firm's objective is to maximize net profit (NP_i) where payment for licenses and the enforcement tax have been deducted, i.e.:

$$NP_i = \pi_i(x_i) - (1-\alpha_i(l_i))pl_i - f\left|x - l\right| \tag{13}$$

First, the firm bids a demand function conditional on this price, $L_i(p)$. After observing the realized equilibrium price (p^*) and resulting license allocation l_i^*, l_{-i}^*, the firm then decides the level of its resource use (x_i). I solve the firm's sequential maximization problem by using backward induction. First, I find the emission that maximizes NP_i conditional on the realized license allocation i.e.:

$$\underset{x_i}{Max}\, NP_i = \pi_i(x_i) - (1-\alpha_i(l_i^*))p^* l_i^* - f\left|x_i + x_{-i} - l^*\right| \tag{14}$$

The derivative with respect to the decision variable is:

$$\frac{dNP}{dx_i} = \begin{cases} \pi_i'(x_i) + f & \text{if } (x_i + x_{-i}^I - l^*) < 0 \\ \pi_i'(x_i) - f & \text{if } (x_i + x_{-i}^I - l^*) > 0 \end{cases} \tag{15}$$

where I assume that the rational firm knows that $dx_{-i}^I / dx_i^I = 0$ because resource use is not observed by other firms.

From (12), the effect of a marginal increase in resource use is to increase firm profit by $\pi_i'(x_i)$ and to change the enforcement tax payment. Whether the enforcement tax payment decreases or increases depends on the sign of the deviation between the aggregate resource use and the total license purchases ($x_i + x_{-i} - l^*$) expected by the firm in the state from which the marginal increase is being considered. If the resource use exceeds the licenses purchased ($x_i + x_{-i} - l^* > 0$) in that state, the enforcement tax payment increases. Because *f* is set higher than the upper bound on firms' marginal profits of resource use (5), we know that $\pi_i'(l_i + x_i^I) \le \pi_i'(0) < f$. This implies that $\pi_i'(x_i) + f < 0$ when $x_i + x_{-i} - l^* > 0$. When license purchases exceed resource use $x_i + x_{-i} - l^* < 0$, then a marginal increase in resource use reduces the enforcement tax payment such that $\pi_i'(x_i) + f > 0$. This is a knife-edge equilibrium with a discontinuity in marginal profit at $x - l^* = 0$, where it jumps from $\pi_i'(x_i) - f < 0$ to $\pi_i'(x_i) + f > 0$ such that:

$$\begin{aligned} \frac{dNP}{dx_i} > 0 \quad &\text{if} \quad x - l^* < 0 \\ \frac{dNP}{dx_i} < 0 \quad &\text{if} \quad x - l^* > 0 \end{aligned} \tag{16}$$

Therefore, it is always optimal for any firm to choose x_i such that $x - l^* = 0$. Thus, only solutions where $x - l^* = 0$ can be Nash equilibria. Although there are an infinite number of such Nash equilibria, there is only one focal equilibrium that firms can hope to coordinate on and that is the equilibrium where all firms purchase precisely the quantity of licenses equal to their own resource use, i.e.

$$x_i = l_i^* \quad \text{for all } i \tag{17}$$

If all firms believe that other firms are rational, it should be possible for the firms to identify and implement the focal equilibrium where all firms comply. The compliance equilibrium has other characteristics that make coordination on it likely, and it turns out that it is possible to allow and facilitate communication between firms that support coordination. I will return to this in the next chapter. For now, I assume that firms are able to coordinate on the full compliance equilibrium and that firms realize this when they submit their license bids.

Continuing the backward induction solution, I find the firms optimal bid table $L_i(p)$ conditional on compliance with the allocated licenses when resource use is decided. For any given license price *p*, the optimal number of licenses to demand will therefore maximize (13) after inserting (19), i.e.,

$$NP_i = \pi_i(l_i) - (1 - \alpha_i(l_i))pl_i \tag{18}$$

Here, the rational firm realizes that the equilibrium license price depends on its own license demand (9) and that, because of this, other firms demand for licenses (10) and the pay-back the firm receives from the regulator (11) also depends on its own license demand. Inserting (9), (10), and (11) into (18) and reducing the maximization problem becomes:

$$\underset{l_i}{Max}\ NP = \pi_i(l_i) - \tilde{D}_i(l_i) \tag{19}$$

where the first order condition implies that:

$$\pi_i'(l_i) = p \tag{20}$$

Inserting (9) and (17), the first order condition for firm I's resource use is:

$$\pi_i'(x_i) = D'(x) \tag{21}$$

which is equivalent to the first order condition for the efficient first best solution (2).

Prior to bidding, a firm is uncertain of the license price, *p*. Because the firm can bid a demand function conditional on *p,* it can neutralize this uncertainty by bidding $l_i = \pi_i'^{-1}(p)$. Thus, conditional on the focal compliance equilibrium, the truthful revelation of demand schedules is a dominant strategy. This is the result in Montero (2008) conditional on full compliance with the allocated licenses. The enforcement portion of the mechanism suggested here simply induces firms to comply with the licenses allocated through the Montero-auction.

As noted by Montero (2008), firms do not need to undertake the calculations above. The regulator can simply inform the firms that truthful revelation is the optimal strategy for each firm, and this can always be verified ex-post (by consultants or the firms' industrial organizations). In our case, the regulator can add that it is also optimal for all firms if all firms comply with their license allocations. Therefore, it is as easy for the individual firm to identify its focal equilibrium strategy in our case as it is for firms to identify their dominant strategy in the case studied by Montero (2008). The key difference is that our case implements in a unique focal Nash equilibrium, not in dominant strategies.

5. Other characteristics of the proposed scheme

A number of other attractive characteristics follow from allocating licenses through a Montero-auction. These properties reinforce the attraction and focal nature of the compliance Nash equilibrium on which the mechanism depends.

Coalitions

Montero (2008) shows that, with the auction scheme, a Pareto optimum with truthful revelation is implemented although firms form coalitions that maximize the aggregated coalition profit. Intuitively, the mechanism induces truthful revelation for all firms and therefore also for a firm consisting of any subset of firms in a coalition. Now I investigate whether a coalition has incentives to deviate from the focal equilibrium strategy. If the focal equilibrium is not threatened by coalitions, Montero's mechanism ensures efficient license allocation under coalitions.

If a coalition consists of *m* firms maximizing aggregate coalition profit, the coalition solves the following problem (using 14) when deciding resource use conditional on license allocation:

$$\underset{x_1,\dots,x_m}{Max}\; NP = \sum_{i=1}^{m} \pi_i(l_i^*) - \sum_{i=1}^{m}(1-\alpha_i(l_i^*))\,p^* l_i^* - f\left|x_i + x_{-i} - l^*\right|) \qquad (22)$$

This equation implies that resource use of coalition firm *i* has a marginal effect on coalition profit of:

$$\frac{dNP}{dx_i} = \begin{cases} \pi_i'(x_i) + nf & \text{if } (x_i + x_{-i}^I - l^*) < 0 \\ \pi_i'(x_i) - nf & \text{if } (x_i + x_{-i}^I - l^*) > 0 \end{cases} \qquad (23)$$

Thus, for coalition firms, the incentive to avoid deviation between the aggregate licenses issued and aggregate resource use is greater than the non-coalition firms' incentives. Of course, a coalition that coordinates license bids may not be as able to coordinate resource use as efficiently because use cannot be observed. However, such coalitions will never be a threat to the focal equilibrium.

Entry and exit incentives

Montero (2008) also shows that, with his scheme, each firm's total tax payment ($\tilde{D}_i(l_i)$) is equal to the total externality a firm imposes on others evaluated at the margin. Under my scheme, the enforcement tax payment in the focal equilibrium is zero; thus, for firm *i* the total tax payment (T_i) is:

$$T_i = \tilde{D}_i(l_i) \qquad (24)$$

Thus, provided firms coordinate perfectly on the focal equilibrium, the proposed mechanism results solely in the tax payment implied by the Montero-auction. Therefore, correct entry and exit incentives are generated.

Coordinating on the focal equilibrium

The focal equilibrium is not a dominant strategy for firms. However, a large number of studies on coordination and bargaining find that outcomes with equitable results are powerful focal points[5]. Because the focal equilibrium results in total tax payments equal to the total damage imposed on other firms, the resulting distribution of tax payments and abatement costs will likely be perceived as fair by most firms. Because this equilibrium is the sole focal equilibrium and is Pareto un-dominated by other equilibria, it is likely highly focal and easy for firms to coordinate on.

If the regulator, in addition, encourages communication (allows collusion), this would further strengthen the incentives to coordinate on the focal equilibrium and provide an

[5] For examples, see Gächter and Riedl (2005), Güth et al (1982), Holm (2000), Nydegger and Owen (1975), Roth and Malouf (1979), Roth and Murnighan (1982), Roth (1995), Schelling (1960), and van Huyck et al (1992), Charness and Rabin (2002), Cox and Sadiraj (2012), Engelmann and Strobel (2006), Poulsen and Poulsen (2012), Güth et al (2012) and Lopez-Perez et al (2013).

effective mechanism for such coordination[6]. This can be done without distorting license allocation because the Montero-auction is collusion-proof.

5. Conclusion

Economists have suggested using aggregate emission taxes to regulate common resources when firms' individual resource use cannot be observed. However, such tax mechanisms are vulnerable to collusion and strategic behavior, and the importance of these vulnerabilities has been demonstrated experimentally. In addition, these mechanisms generate inefficient entry-exit incentives. Instead, I suggest combining a Montero auction mechanism for allocating licenses for use of the commons with a tax on aggregate unlicensed commons use. This suggested scheme is attractive because it is collusion-proof, ensures truthful revelation and generates efficient entry-exit incentives. The main weakness of this scheme is that it implements in a unique focal Nash equilibrium, not in dominant strategies. Experimental evidence suggests that the focal equilibrium on which the proposed scheme depends may be stable, and that stability can be strengthened by encouraging communication between regulated firms without inducing allocation distortions. The natural next step for investigating the suggested mechanisms usefulness is experimental investigation.

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