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## Abstract

As with other commodity markets, markets for trading pollution permits have not been immune to market power concerns. In this paper, I survey the existing literature on market power in permit trading but also contribute with some new results and ideas. I start the survey with Hahn's (1984) dominant-firm (static) model that I then extend to the case in which there are two or more strategic firms that may also strategically interact in the output market, to the case in which current permits can be stored for future use (as in most existing and proposed market designs), to the possibility of collusive behavior, and to the case in which permits are auctioned off instead of allocated for free to firms. I finish the paper with a review of empirical evidence on market power, if any, with particular attention to the U.S. sulfur market and the Southern California NOx market.

Keywords: market power, emissions trading, pollution permits, storable permits

*JEL* codes: D40, L13, Q58

## 1 INTRODUCTION

Markets for trading pollution rights or permits have attracted increasing attention in the last decades. The best example is the carbon trading mechanisms of the Kyoto Protocol for dealing with global warming but there are many other experiences.<sup>1</sup> As with other commodity markets,

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<sup>1</sup>Analysis of the U.S. sulfur market can be found in Ellerman et al (2000), of the California NOx market in Holland and Moore (2008), of the E.U. Emissions Trading System in Ellerman and Joskow (2008), and of other permit markets in Tietenberg (1985 and 2006).

permit markets have not been immune to market power concerns (e.g., Tietenberg, 2006); that is, the ability of large players to move prices, either unilaterally or collectively. While some of the existing permit markets are composed by many small agents (e.g., the particulate market in Santiago-Chile),<sup>2</sup> others are not. In the U.S. sulfur market, for example, 43% of the permits corresponding to the 1995-99 phase were allocated to four firms. In the global carbon markets that will develop under the Kyoto Protocol and possibly beyond there will be countries with large shares of permits. In fact, Kyoto allocates a fifth of the (Annex I) permits to Russia and a third to the U.S.

Some readers may argue that market power should be less of a concern in a global carbon market because the permits will end up distributed among countless facilities around the world; none of which with the size to move the market by itself or with the incentives to be part of a cartel with hundreds of members. But even when a country member ends up allocating its carbon quota to its domestic firms, which can then be freely traded in the global market, the country can simultaneously resort to alternative domestic policies to "coordinate" the actions of its domestic firms very much like a large agent would do. For example, a country that wants to exercise downward pressure on prices can set a domestic subsidy on cleaner but more expensive technologies (e.g., some of the renewable energies), and thus, reducing the country's aggregate demand for permits in the global market. On the other hand, a country that wants to exercise upward pressure on prices can levy a tariff on permit exports, and thus, depressing the country's aggregate supply of permits. It would be hard to argue against such a measure if the resulting revenues are aimed at financing R&D on cleaner technologies.<sup>3</sup>

There is another reason to believe that countries/regions —not individual facilities— are the relevant players for understanding the exercise of market power in a global market for carbon permits. As argued by Jaffe and Stavins (2009), it is very unlikely to see, at least in the medium-term, a truly global carbon market with a unique market price but rather multiple permit markets in different countries/regions. These markets will be (imperfectly) linked to each other so that some exchange of permits will be allowed across markets. Countries, not individual facilities, will decide through different domestic policies how much "linkage" to have with the rest of the world. Hence, the interesting question is under what circumstances a large country would find in its best interest to implement domestic policies or market designs (i.e.,

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<sup>2</sup>For a complete description of this program see Montero et al. (2002).

<sup>3</sup>Alternatively, a country can exercise downward pressure on prices by lowering the actual price faced by its domestic firms; for example, by giving credits for permits redeemed at compliance.

introduction of safety valves, subsidies, standards, etc.) that would work as if the country were exercising market power in a truly global market. Or alternatively put, if we observe the implementation of domestic policies that prevent a perfect linkage among the different permit markets to what extent we can claim that these policies are driven by a genuine interest in altering international prices or rather they are the result of internal domestic forces (politics) unrelated to market power.

Answers to the above questions requires, at least, understanding of how and to what extent a large agent, either acting individually or collectively, can move prices away from competitive levels (at times I will exchange strategic agent for large agent and firm for agent or player). Starting with Hahn's (1984) pioneering article, there is a significant amount of work now addressing these matters. This survey article reviews that literature. With few exceptions, which I cover at the end, the survey is mainly theoretical. As observed in almost all existing markets, for most part of the survey I work under the assumption that permits are allocated for free to firms. I do however, discuss how results change when permits are auctioned off. In this same section I let the regulator know little about firms' relevant characteristics (i.e., abatement costs). In the concluding section I briefly touch on some instrument choice considerations; for example, the extent to which a permit instrument may look inferior to alternative instruments (e.g., taxes) because of potential market power problems. In addition, I assume throughout that pollution is perfectly observable by the regulator (i.e., no hidden action) and that there is complete enforcement of the regulation.<sup>4</sup>

The rest of the paper proceeds as follows. In the next section, Section 2, I present the basic problem of a large polluting firm and a fringe of small polluting firms in a static setting. In Section 3, I extend the basic model to allow for two or more large firms that may also interact in imperfectly competitive output markets. In Section 4, I consider a dynamic permit market with storable permits and allocations that decline over time, so in principle, agents can smooth compliance costs by storing current vintage permits for later use. In Section 5, I drop the assumption that permits are grandfathered to firms and assume instead that they are auctioned off. The scant empirical evidence on market power in permit trading is reviewed in Section 6. Concluding remarks are in Section 7.

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<sup>4</sup>See van Egteren and Weber (1996) and Chavez and Stralund (2003) for extensions of Hahn's (1984) model to the case of incomplete enforcement. There seems to be no paper, however, studying market power in the presence of moral hazard (i.e., imperfect monitoring of emissions).

## 2 THE BASIC MODEL

Hahn (1984) was the first to formally study market power in permit trading. He considers a large polluting firm and a fringe of small polluting firms in a static framework. Hahn (1984) abstracts from the output market by assuming that all polluting firms take output prices as given. Pollution permits are allocated for free to firms and must be used in the same period for which they were issued. So, even if firms interact for several periods the restriction that permits cannot be stored for future use and/or that firms cannot borrow from future allocations make it a static problem (this is not necessarily the case if instead of having one large firm we have a few large firms trying to sustain collusion from their repeated interactions). Hahn (1984) shows that market power vanishes when the permit allocation of the large agent is exactly equal to its "efficient allocation", i.e., its emissions under perfectly competitive pricing. Hence, an allocation different than the efficient allocation results in either monopoly or monopsony power.

To formally see Hahn's insight consider a period with two stages. In the first stage, the large firm, which we denote by "m", announces a permits spot sale or purchase of  $x_m$  (we will adopt the convention that  $x > 0$  for sales and  $x < 0$  for purchases). Having observed  $x_m$ , fringe firms, which we denote by "f", clear the market in the second stage by buying/selling  $x_f = -x_m$  permits. Let  $C_m(q_m)$  be the large firm's cost of abating  $q_m$  units of pollution from some unrestricted level of emissions  $u_m$  to  $e_m = u_m - q_m$  and where  $C'_m > 0$  and  $C''_m > 0$ . Similarly, let  $C_f(q_f)$  be the fringe's aggregate cost of abating pollution from the unrestricted level  $u_f$  to  $e_f = u_f - q_f$  and where  $C'_f > 0$  and  $C''_f > 0$ . In addition, let  $a^m$  and  $a^f$  be the permit allocations to the large firm and fringe firms, respectively. To make the problem relevant  $a^m + a^f < u^m + u^f$ . In deciding its spot sale/purchase, the large firm, acting as a Stackelberg leader, solves

$$\max_{x_m} p(x_m)x_m - C_m(q_m) \tag{1}$$

where  $p(x_m)$  is the market clearing price.

Fringe firms operate along their static reaction function, that is,  $p(x_m) = C'_f(q_f)$ , where  $q_f = u_f - a_f - x_m$ . Likewise, full compliance requires  $q_m = u_m - a_m + x_m$ . Replacing these expressions into (1) and solving we obtain the equilibrium condition

$$C'_f(q_f) - x_m C''_f(q_f) - C'_m(q_m) = 0 \tag{2}$$

that requires marginal revenues (the first two terms) to be equal to marginal costs. If in

equilibrium  $x_m = 0$ , then we obtain the perfectly competitive pricing condition of equating marginal costs across firms. For  $x_m = 0$  to happen in equilibrium we require the allocation  $a_m$  to be exactly equal to the large firm's perfectly competitive emissions, that is,  $e_m^* = u_m - q_m^*$ , where  $q_m^*$  solves  $C'_f(q_f^*) = C'_m(q_m^*)$ . In this case, only fringe firms engage in permit trading clearing the market at  $p = C'_f(q_f^*)$ . When  $a_m > e_m^*$ , the large firm exercises monopoly power by selling less and abating more than what is socially efficient. Conversely, when  $a_m < e_m^*$ , the large firm exercises monopsony power by buying less and abating more than what is socially efficient.

Starting with Hahn, market power in permit trading has always been understood as how the initial allocation of free permits affect firms' compliance and trading decisions. So, in principle, a completely informed regulator could alleviate market power concerns by allocating permits in a cost-effective manner. But rarely that completely informed regulator exists, and if it does, political economy considerations (e.g., Joskow and Schmalensee, 1998) prevents him to constantly making allocation adjustments as to stick to a cost-effective allocation rule. While extremely insightful, Hahn's model provides incomplete understanding of market power in more real-world settings, namely, when there two or more strategic firms, when large polluters also interact in (concentrated) output markets, when agents are engaged in dynamic and/or repeated interactions, and when part or all of the permits are not allocated for free but auctioned off. We turn to those cases now.

### 3 EXTENDING THE BASIC MODEL

In this section we extend the basic model to allow for two or more strategic agents that may or may not interact in the output market but retain the static nature of their interactions.

#### 3.1 Multiple Strategic Agents

For now let us keep the assumption that the output market is perfectly competitive but consider that there are two or more large agents buying and selling permits. This would apply, for example, to permits markets with few polluting agents that sell their output in international (large) markets or at regulated prices. (I will later introduce a case of three paper and pulp mills and two wastewater treatment plants discharging biochemical oxygen demand into a river in southern Chile).

A natural way to handle multiple large firms would be through a straightforward transformation of Hahn's model into a Cournot-type game. I believe this approach was first used by Westskog (1996) to investigate market power in an international carbon market with countries as players. For simplicity consider two large firms,  $i$  and  $j$ , and a competitive fringe. We maintain the notation and timing of the basic model, i.e.,  $i$  and  $j$  decide first and simultaneously their permit sales/purchases  $x_i$  and  $x_j$  and then fringe firms clear the market. The Nash equilibrium of the game is found by solving for both  $i$  and  $j$

$$\max_{x_i^i} p(x_i, x_j)x_i - C_i(q_i)$$

where  $p(x_i, x_j) = C_f'(q_f)$ ,  $q_f = u^f - a^f - x_i - x_j$  and  $q_i = u_i - a_i + x_i$ . In equilibrium, marginal revenues must be equal to marginal costs, that is

$$C_f'(q_f) - x_i C_f''(q_f) - C_i'(q_i) = 0 \quad (3)$$

for both  $i$  and  $j$ . Consistent with Hahn, market power disappears only when each and every strategic firm receives an allocation exactly equal to its cost-effective pollution level, i.e.,  $a_i = e_i^*$  for all  $i$ .

Some observations are worth noting about this oligopoly-fringe model. The first is that the fringe must be rather large for the model to work well. Unlike the Cournot model or Hahn's model, the oligopoly-fringe model does not have a clearing price for the case in which large firms' net position cannot be absorbed by the fringe. It is not obvious that the price would go to the backstop price (i.e., price at which firms can switch to a zero-emissions technology) when the fringe is short in permits, i.e.,  $-x_i - x_j = x_f > a_f$ , or that the price would collapse to zero when there is an excess of permits, i.e.,  $x_i + x_j = -x_f > u_f$ . More importantly, even if we restrict large firms' action space to  $-a_f < x_i + x_j < u_f$ , the model has poor predictive capabilities. An example may clarify things. Take, for example,  $C_i(q) = C_j(q) = q^2$ ,  $u_i = u_j = 1$ ,  $C_f(q) = \gamma q^2$  and  $u_f = u$ . The regulatory goal is to halve pollution from its unrestricted levels, that is,  $a_i + a_j + a_f = 1 + u/2$ . Consider first the case in which the fringe of polluters is comparable to one of the strategic firms in terms of cost and unrestricted emissions ( $\gamma = u = 1$ ) and  $a_i = 1$ ,  $a_j = 0$  and  $a_f = 1/2$ . The oligopoly-fringe model predicts an equilibrium price equal to the cost-effective level,  $p = 1$ , and trading volume by the large firms equal to  $x_i = -x_j = 1/4$ ,

which is half the cost-effective level.<sup>5</sup> On net, the fringe does not trade since it receives its cost-effective allocation. Here the model seems to capture large agents' behavior reasonably well: large agents want to trade less than they would in perfect competition.

Let us now consider an almost negligible fringe:  $u = 10^{-3}$ ,  $a_f = 5 \times 10^{-4}$  and  $\gamma = 10^3$ . The oligopoly-fringe model still predicts the cost-effective price,  $p = 1$ , and not trading by the fringe (i.e., fringe has just enough permits to cover its emissions when  $p = 1$ ). However, it predicts virtually no trading activity by the large firms,  $x_i = -x_j = 5 \times 10^{-4}$ , which implies that in equilibrium  $q_i \approx 0$  and  $q_j \approx 1$ . The logic is simple. Since the fringe's response becomes infinitely elastic when it vanishes (i.e.,  $|p'|$  or  $C_f'' \rightarrow \infty$ ), a large seller (buyer) wants to sell (buy) virtually nothing in order to prevent a high drop (increase) in prices. By forcing large firms to satisfy (3) regardless of the fringe's size, the model rules out by construction any bilateral interaction among large firms, which would be a main trading channel in a market with a small fringe. Thus, the oligopoly-fringe model produces an unreasonably expensive abatement pattern. In the example above, the oligopoly-fringe model predicts aggregate abatement costs twice as large as if we let firms to Nash-bargain over the permits.

In a forthcoming paper, Malueg and Yates (2009) develop a model that deals precisely with a permit market in which there are only strategic players.<sup>6</sup> They do not motivate their paper upon the observation that the oligopoly-fringe model works poorly but rather upon the observation that for some permit markets the oligopoly-fringe structure may not apply. The water-pollution problem mentioned above is a good example. Borrowing from the work of Hendricks and McAfee (2009), which, in turn, is based on the supply-function-equilibria model of Klemperer and Meyer (1998), Malueg and Yates (2009) consider a game in which a number of strategic polluters submit a linear net-trade schedule to a "market maker", which aggregates schedules and clears the market at a uniform price  $p$ . For a given initial allocation of permits, a net-trade schedule indicates how many (additional) permits the firm is willing to buy/sell as a function of the clearing price  $p$ . Since the total amount of permits is fixed, the model is very close to the auction of shares of Wilson (1979). The authors' model also imposes Wilson's restrictions of linear schedule and one degree of freedom (in Wilson's model firms can only vary the slope of their bidding schedules while in the authors' model they can only vary the

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<sup>5</sup>The cost-effective solution is given by  $q_i = q_j = q_f = 1/2$  and  $p = 1$ . The fact that the oligopoly-fringe model predicts the cost-effective price is a consequence of the symmetry of the problem. For example, the equilibrium price would drop to  $3/4$  if instead we use  $a_i = 1/2$ ,  $a_j = 0$  and  $a_f = 1$ .

<sup>6</sup>Using a similar approach, Lange (2008) also let all polluting agents, regardless of their size, be strategic agents.

intercept).<sup>7</sup>

Malueg and Yates' (2009) model is a valuable addition towards our understanding of market power in oligopoly environments. Like in Wilson (1979), the model has a unique equilibrium where buyers find it optimal to report schedules below their true ones —as an attempt to lower prices— and sellers find it optimal to do just the opposite. Because of this strategic reporting, the amount of trading activity is below the cost-effective level but, unlike in the oligopoly-fringe model, still positive and significant. As we increase the number of strategic firms, we approach truthful reporting and with that cost-effectiveness. As in Hahn, cost-effectiveness can be also be obtained for any number of firms with an allocation that exhibits no trading in equilibrium. Despite these reasonable predictive properties, Malueg and Yates' (2009) model is not entirely satisfactory either. To start, the model predicts an equilibrium price exactly equal to the cost-effective level for any number of firms and regardless of the initial allocations of permits. This is in part due to restriction of linear schedules with one degree of freedom (I wonder whether this result would change if instead of the intercept firms were able to freely choose the slope; also, letting the slope vary instead of the intercept makes it possible to add a fringe of suppliers).

Other than for modeling convenience, there is no reason to restrict a firm's decision to a single variable. But if we let firms freely choose the slope and intercept of their (still) linear net-trade schedules that would most probably result —as shown by Milgrom (2005) for the Wilson's share auction— in multiple equilibria including the perfectly competitive one. I see nothing particular in permit trading that could rule out the multiplicity. That would leave us with rather weak theories of permit trading in oligopoly settings. The problem is that if empirical estimations show indeed departure from marginal cost pricing we would not be sure how much of this departure is caused by the initial allocation of permits and how much by reasons not captured by current models. It would be hard to write policy prescriptions regarding allocations when we do not know the answer to this question.

### 3.2 Interaction with the Product Market

Hahn (1984) assumes that polluting firms sell their the products in perfectly competitive markets. In some cases this may not be a good assumption. Some of the large countries in an eventual global carbon market are also big players in energy markets (e.g., Hagem and Maes-

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<sup>7</sup>More precisely, Wilson's model can be interpreted as one in which firms' only choice is the slope of their (linear) bidding schedules after their intercepts have been fixed at  $1/(n-1)$ , where  $n$  is the number of firms.

tad, 2005). The NOx permit market in California is another example. Nearly 25% of the NOx permits were allocated to facilities that sell power into the California electricity market, which has been recognized for its (unilateral) market power problems (e.g., Borenstein et al., 2002; Joskow and Kahn, 2002). In fact, Kolstad and Wolak (2008) argue that electric utilities used the NOx market to enhance their ability to exercise (unilateral) market power in the electricity market. I will come back to this result in Section 6.

The interesting question here is how a permits market may exacerbate market power problems in other markets and vice versa.<sup>8</sup> Misiolek and Elder (1989) were the first to notice that in addition to the Hahn's effect there may be incentives for large firms to manipulate the permits market in an effort to raise their rival's costs in the output market —just like in Salop and Scheffman (1983). Extending Hahn's market structure to the output market, Misiolek and Elder (1989) argue that the large firm now has incentives to sell less (or buy more) than in Hahn's pollution-trading model. The authors note that depending on the initial allocation of permits, this additional strategic effect can sometimes worsen and sometimes alleviate the inefficiencies identified by Hahn. Sartzetakis (1997) and von der Fehr (1993), among others, extend the insights of Misiolek and Elder (1989) to oligopolistic settings and discuss when raising rivals' costs could be in fact a profitable strategy.<sup>9</sup>

My problem here is that unlike previous authors I do not see so clearly that the raising rivals' costs effect can alter the permits trading pattern in a significant way as to be able to infer something from the empirical data. Based on the insights of Misiolek and Elder (1989), for example, one may argue that all else equal a large polluting source exercising (unilateral) market power in the output market is more likely to be a buyer of permits than an equally large polluting source acting competitively in the output market. It is interesting to notice that some of the large polluting sources in the U.S. sulfur market sell their output in concentrated deregulated electricity markets and happen to be net buyers in the permits market (more on the sulfur market in Section 6). Can this empirical observation be interpreted as an indication of market power in both markets? I do not think the theory supports that claim.

A simple extension of Hahn's model may clarify my point. Let the large firm's output

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<sup>8</sup>See Requate (2005) for a complete discussion on the performance of other environmental policy instruments such as taxes and standards in the presence of imperfectly competitive output markets.

<sup>9</sup>Motivated by the structure of the EU ETS market, Sanin and Zana (2009) study a different yet interesting problem. They look at the interaction of a continuum of imperfectly competitive output markets with a perfectly competitive permits market. They show that because of imperfect competition in the output markets there may be cases in which permit prices can increase with the adoption of cleaner technologies.

be denoted by  $y_m$  and the fringe's by  $y_f$ . For simplicity production costs are separable from abatement costs and are denoted by  $K_m(y_m)$  and  $K_f(y_f)$ , respectively. Unrestricted emissions are equal to  $u_m = y_m$  and  $u_f = y_f$ . This pollution-production characterization would fit well the U.S. sulfur and California NOx markets, for example. Acting as a Stackelberg leader in both the permit and output market,<sup>10</sup> the large firm announces first how many permits to trade,  $x_m$ , and how much output,  $y_m$ , to bring to the product market. Having observed that, fringe firms announce their output,  $y_f$ , and clear the permits market by buying  $x_f = -x_m$ . Consumers clear the output market according to the inverse demand  $R(y_m + y_f)$ . The equilibrium solution can be found by maximizing the large firm's profits

$$\max_{x_m, y_m} p(x_m)x_m + R(y_m + y_f)y_m - K_m(y_m) - C_m(q_m) \quad (4)$$

subject to the equilibrium conditions  $p(x_m) = C'_f(q_f)$  and  $R(y_m + y_f) = K'_f(y_f) + C'_f(q_f)$ . Note that the latter condition requires that at the margin the output price must cover fringe's production and abatement costs.

The equilibrium outcome can be found by backward induction as follows. For a given a transfer of  $x_m$  permits from the large firm to the fringe at the competitive price  $p(x_m)$ , which will be determined later, the large firm solves

$$\max_{y_m} R(y_m + y_f)y_m - K_m(y_m) - C_m(q_m)$$

leading to the first-order condition (recall that  $q_m = y_m - a_m + x_m$ )

$$R + R'(\cdot) \left( 1 + \frac{dy_f(y_m)}{dy_m} \right) y_m - K'_m(y_m) - C'_m(q_m) = 0 \quad (5)$$

where  $dy_f(y_m)/dy_m = R'/(K'_f + C'_f - R') < 0$  captures the fringe's downward sloping reaction function to an increase in the large firm's production.<sup>11</sup> Solving we obtain the (subgame) equilibrium quantities as a function of  $x_m$ :  $y_m(x_m)$ ,  $y_f(x_m)$ ,  $q_m(x_m) = y_m(x_m) - a_m + x_m$  and  $q_f(x_m) = y_f(x_m) - a_f - x_m$ .

Moving backwards, the large firm now chooses  $x_m$  to maximize (4) but anticipating the

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<sup>10</sup>Results do not qualitatively change if we let firms to simultaneously announce their production quantities.

<sup>11</sup>The expression for  $dy_f/dy_m$  is obtained from totally differentiating the equilibrium condition  $R(y_m + y_f) = K'_f(y_f) + C'_f(q_f)$  with respect to  $y_m$  and using  $q_f = y_f - a_f - x_m$ . Further,  $dy_f/dy_m$  would have been zero had we assumed simultaneous move in the output market.

effect that its choice will have subsequently on output and abatement. Using the envelope theorem and  $p(x_m) = C'_f(q_f)$ , the FOC for  $x_m$  becomes

$$C'_f(q_f) - C''_f(q_f) \left\{ 1 - \frac{dy_f}{dx_m} \right\} x_m - C'_m(q_m) + R'y_m \left[ \frac{dy_f}{dx_m} - \frac{dy_f(y_m)}{dy_m} \frac{dy_m(x_m)}{dx_m} \right] = 0 \quad (6)$$

Expressions for  $1 > dy_f(x_m)/dx_m > 0$  and  $-1 < dy_m(x_m)/dx_m < 0$  can be obtained by totally differentiating (5) and  $R(y_m + y_f) = K'_f(y_f) + C'_f(q_f)$  with respect to  $x_m$ .<sup>12</sup> The new terms not included in Hahn's model, i.e., equation (3), are in brackets. The curly bracket is less than one, although still positive, capturing the fact that the permit price is less sensitive to changes in  $x_m$  because the fringe now accommodates both output and abatement. This *demand* effect induces the large firm to sell more permits than otherwise because it would not fall as much. The last term in (6) captures the raising rival's cost effect, which has the opposite sign, that is, it induces the large firm to sell fewer permits than otherwise. Selling permits to the fringe increases its output supply ( $dy_f/dx_m > 0$ ) which in turn depresses the output price  $R$ . As indicated by the second term in the square brackets, this effect is somehow diminished by the Stackelberg timing in the output market; under Cournot timing  $dy_f(y_m)/dy_m = 0$ .

It is hard to see from (5) and particularly (6) the extent to which the introduction of the output market alters the trading pattern of the large firm. For that let us adopt some functional forms and numbers. Let  $C_m(q) = C_f(q) = q^2$ ,  $K_m(y) = C_f(y) = y^2$ , and  $R(y_m + y_f) = 10 - y_m - y_f$ . Suppose further an environmental constraint equal to  $a_m + a_f = 2$ . Given the symmetry of the problem we know from Hahn that when the large firm behaves competitively in the output market an even allocation of permits, i.e.,  $a_m = a_f = 1$ , would lead to competitive pricing in both markets.<sup>13</sup> The perfectly competitive outcome is presented in the first column of Table 1. If we now return to our model of market power in both markets, we observe in the second column of Table 1 that both equilibrium prices are above competitive levels but the amount of permit trading has remained unchanged at zero.<sup>14</sup> In terms of the amount of

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<sup>12</sup>Note also that

$$\frac{dy_f(y_m)}{dy_m} \frac{dy_m(x_m)}{dx_m} \neq \frac{dy_f(x_m)}{dx_m}$$

To see why note that had we assumed Cournot timing in the output market  $dy_f(y_m)/dy_m$  would have been zero but  $dy_f(x_m)/dx_m$  would have been still positive.

<sup>13</sup>Formally, under competitive pricing equation (5) changes to  $R = K'_m(y_m) + C'_m(q_m)$  and (6) to

$$C'_f(q_f) - C''_f(q_f) \left\{ 1 - \frac{dy_f}{dx_m} \right\} x_m - C'_m(q_m) + R'y_m \left[ \frac{dy_m}{dx_m} + \frac{dy_f}{dx_m} \right] = 0$$

And for our symmetric-linear setting we have  $dy_m/dx_m = -dy_f/dx_m = -1/2$ .

<sup>14</sup>Note that for the adopted functional forms we have  $dy_m/dx_m = -3/7$  and  $dy_m/dx_m = 17/35$ .

permit trading, the raising rival's cost effect has been fully offset by both the demand effect already detected in equation (6) but also by the large firm's (strategic) output contraction which increases its permits supply. This full-offsetting result carries on to different permits allocations, as shown in the remaining columns of Table 1. Obviously this result is in part specific to our setting but it does raise the issue that is not evident how the introduction of imperfect competition in the output market changes the way large firms trade permits. It seems that the empirical test that one would apply to the data, when available, must be very specific to the case in hand.

## 4 DYNAMIC INTERACTIONS

We now take our discussion to a dynamic setting. This is relevant when permits are storable, as occurs in most markets, and/or when two or more strategic firms are engaged in a repeated interaction. I discuss both cases next.

### 4.1 Storable Permits

A common feature in most existing and proposed pollution market designs is the future tightening of emission limits accompanied by firms' possibility to store today's unused permits for use in later periods. This design was used in the U.S. sulfur market but global trading proposals for dealing with carbon dioxide emissions will likely have similar characteristics.<sup>15</sup> It is true that we do not know yet the type of regulatory institutions —including policy instruments and participants— that will succeed the Kyoto Protocol in the multinational efforts to stabilize carbon emissions and concentrations in the atmosphere. At this point all we know is that regardless of the regulatory mechanism adopted, there will be a long transition period of a few decades between now and the time of stabilization. But if this transition period is governed by a Kyoto-type market mechanism, then, the global carbon market that will eventually develop will have many of the properties that are discussed in this section. In anticipation of a tighter emission limit, it is in the firms' own interest to store permits from the early permit allocations and build up a stock of permits that can then be gradually consumed until reaching the long-run emissions limit. This build-up and gradual consumption of a stock of permits give

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<sup>15</sup>Already in the early programs of the 1980s like the U.S. lead phasedown trading program and the U.S. EPA trading program firms were allowed to store permits under the so-called "banking" provisions – provisions that were extensively used (Tietenberg, 2006).

rise to a dynamic market that shares many, but not all, of the properties of a conventional exhaustible-resource market (Hotelling, 1931).

Using a two-period model, Hagem and Westskog (1998) were the first to consider this dynamic problem for the Hahn's market structure.<sup>16</sup> Unfortunately, a two-period model leaves important elements outside the analysis; for example, the possibility of a period of time in which only one firm is holding stock. In a forthcoming paper, Liski and Montero (2009a) study the subgame properties of the equilibrium path of a multi-period permit market with Hahn's structure. Agents, the large firm and the competitive fringe, receive for free a very generous allocation of permits for a few periods and then an allocation equal, in aggregate, to the long-term emissions goal established by the regulation, which is given by the (constant) flow allocation  $a^m + a^f$ . The generous allocation of the first few periods is captured by a (one-time) stock allocation of  $s_0 = s_0^m + s_0^f$ . Liski and Montero (2009a) are particularly interested in understanding the exercise of market power during the transition phase, i.e., during the stock depletion phase, and how it depends on the initial distribution of the stock,  $s_0^m$  and  $s_0^f$ , among the different parties. The existing literature provides little guidance on how individual endowments relate to market power in a dynamic setting with storable endowments. Agents in their model not only decide on how to sell the stock over time, as in any conventional exhaustible-resource market, but also how to consume it as to cover their own emissions. In addition, since permits can be stored at no cost (other than the opportunity cost), agents are free to either deplete or build up their own stocks.

If we let  $\bar{p}$  be the long-run equilibrium price of permits,<sup>17</sup> Liski and Montero (2009a) find that when the large firm receives a sufficiently large fraction of the initial stock, this agent becomes a net seller of permits along a subgame perfect equilibrium path that is qualitatively not different than the path followed by a large seller of a conventional exhaustible resources with a choke price of  $\bar{p}$  (Salant, 1976).<sup>18</sup> As shown in Figure 1, the manipulated equilibrium

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<sup>16</sup>The perfectly competitive solution was already documented by Rubin (1996).

<sup>17</sup>To concentrate exclusively on market power during the transition phase assume that  $a^m$  and  $a^f$  are cost-effective allocations, that is,

$$\bar{p} = C'_m(q_t^m = u^m - a^m) = C'_f(q_t^f = u^f - a^f)$$

Alternatively, one can assume that the long-run emissions goal is sufficiently tight that the long-run equilibrium price is fully governed by the price of backstop technologies, which would be  $\bar{p}$ . This seems to be a reasonable assumption for the carbon market. Nevertheless, Liski and Montero (2009a) allowed for long-run market power in one of their extensions.

<sup>18</sup>Note that Liski and Montero's (2009a) model is very different from Salant's in that they view firms as coming to the market in each period instead of making a one-time quantity-path announcement at the beginning of the game.

price path  $p^m$  is initially higher than the competitive level (denoted by  $p^*$ ) and grows at the rate of interest,  $r$ , as long as the fringe is holding stock. Right after the fringe stock is exhausted at  $T^f$ , the manipulated price grows at a lower rate. As a monopoly stockholder, the large firm is now equalizing marginal revenues rather than prices in present value until the end of the storage period,  $T^m$ . The dashed line shows how marginal revenues, which are equal to marginal costs in each period, evolve over time. The exercise of market power implies extended overall exhaustion time,  $T^m > T^*$ , where  $T^*$  is the socially optimal exhaustion period for the overall stock  $s_0$ , as defined by the Hotelling (arbitrage, terminal and exhaustion) conditions. Thus, the large agent manipulates the market by saving too much of the stock, which shifts the initial abatement burden towards the fringe and leads to initially higher prices.

When  $s_0^m$  is sufficiently large for the large firm to be a net seller during the depletion (i.e., transition) phase, the latter has no problems in solving the two-dimensional objective of intertemporal permit revenue maximization and abatement cost minimization in a credible (i.e., subgame-perfect) manner. As we reduce the initial stock allocation to the large agent (and increase  $s_0^f$ ), there is a point in which the revenue maximization objective drops out and the large agent stops trading with the rest of the market; it only uses its stock to minimize costs while reaching the long-run emissions target  $a^m + a^f$ . This point is when  $s_0^m$  is exactly equal to the "efficient allocation", i.e., the allocation profile that would cover the large agent's emissions along the perfectly competitive path.

When the large agent's stock falls below its efficient allocation, and hence, becomes a net buyer in the market, it has great difficulties in credibly committing to a purchasing path that would keep prices below their competitive levels as Hahn's monopsonist would do. The large agent suffers from a Coase conjecture (Coase, 1972; Bulow, 1982). Any effort to depress prices below competitive levels would make fringe members to maintain a larger stock in response to their (correct) expectation of a later appreciation of permits. Figure 2 may help. The perfectly competitive price path is again denoted by  $p^*$ . Ask now, what would be the optimal purchase path for the large agent if it could fully commit to it at time  $t = 0$ ? Since letting the large agent choose a spot purchase path is equivalent to letting it go to the spot market for a one-time stock purchase at time  $t = 0$ , conventional monopsony arguments would show that the large agent's optimal one-time stock purchase is strictly smaller than its purchases along the competitive path  $p^*$ . The new equilibrium price path would be  $p_2$  and the fringe's stock would be exhausted at  $T_2 > T^*$ . The large agent's internal price (i.e., its marginal cost), on the other

hand, would move along path  $p_1$  and its own stock would be exhausted at  $T_1 < T^*$  (recall that all three paths  $p^*$ ,  $p_1$  and  $p_2$  rise at the rate of interest). But players come to the spot market more than once implying that  $p_1$  and  $p_2$  are not time consistent (i.e., they violate subgame perfection). The easiest way to see this is by observing that at time  $T_1$  the large agent would like to make additional purchases, which would drive prices up. Since fringe members anticipate and arbitrate this price jump, the actual equilibrium path would lie somewhere between  $p_2$  and  $p^*$  (and  $p_1$  closer to  $p^*$  as well). Moreover, since the large agent has the opportunity to move not twice but in each and every period, one can very well conjecture that the time-consistent path may come close, if not equal, to the perfectly competitive path  $p^*$ .

In a related paper, Liski and Montero (2009b) study the subgame perfect equilibrium of the more conventional problem of a monopsonist of an exhaustible-resource playing against a fringe of suppliers that have no internal demand for the resource. Unlike in the durable-good-monopoly analog, they show that the monopsonist can indeed depress prices in (subgame perfect) equilibrium but at the expense of delaying the adoption of the backstop technology (i.e., reaching the price of a substitute at which demand for the exhaustible resource disappears). As this latter cost increases, the subgame perfect equilibrium comes closer to the perfectly competitive one. But if the adoption of the backstop technology reports no benefit to the monopsonist (i.e., zero cost of postponing its adoption), the latter can credibly postpone the adoption of the backstop technology indefinitely, and hence, commit to the monopsony price path—very much like a durable good monopolist that can credibly commit to the monopoly path when it faces a stock of consumers with constant valuation.

The pollution model of Liski and Montero (2009a) is somehow different than the one in Liski and Montero (2009b) for two reasons specific to the pollution context: (i) the presence of many small polluting agents that free-ride on the large agent’s effort to depress permit prices (i.e., the seller side is also consuming from the remaining stock of permits) and (ii) the substantial cost the large agent may incur from postponing the arrival of the long-run equilibrium (unless the long-run goal is a total phase out of pollution). Because of these two reasons the scope for market (buyer) power is considerably reduced in the pollution market.

A numerical example may help to illustrate how the market dynamics introduced by the stock allocations brings a sharp distinction between the seller and the buyer (which does not arise in Hahn’s static context). The large agent and the fringe are identical in all respects but in stock allocations. We assume linear marginal costs,  $C'_m(q) = C'_f(q) = q$ , and constant

unrestricted emissions,  $u^f = u^m = 2$ . In each period  $t \in [0, \infty)$ , firms receive a flow allocation equal to  $a^f = a^m = 1$ . In addition to the flow allocations, firms receive an overall stock allocation at  $t = 0$  of  $s_0 = s_0^f + s_0^m = 5$ . The (continuous-time) interest rate is  $r = 0.1$ . Note that because of the symmetry in costs and allocations, in the long-run, i.e., once stocks have been fully depleted, firms are in perfect competition ( $\bar{p} = q^f = q^m = 1$ ). The idea of the numerical exercise is to compare the perfectly competitive path (that results from stock allocations  $s_0^f = s_0^m = 2.5$ ) to the subgame perfect paths associated to two extreme stock allocations: (i) the large agent receives no stock (pure monopsony:  $s_0^m = 0$ ) and (ii) the large agent receives the full stock (pure monopoly:  $s_0^m = 5$ ).

In carrying out the exercise it is useful to start with the artificial assumption that the large agent is restricted to trade only once with the market at  $t = 0$  (the large agent can and will engage in a stock transaction). In the monopsony case, the large agent buys 1.79 units of the overall stock at  $t = 0$  leading to the paths of Figure 2 with  $T_1 = 6.6$  and  $T_2 = 9.2$  (note also that  $T^* = 8.0$ ). The same paths of Figure 2 serve to explain the monopoly solution as well: the large agent sells only 1.44 units of its stock to the fringe, so he internally follows path  $p_2$  exhausting at  $T_2 = 9.8$  while the fringe follows path  $p_1$  exhausting at  $T_1 = 5.9$ . It is not surprising from what we know from the static model, that the monopoly and monopsony solutions in this (artificial) one-shot game almost mirror each other with similar welfare consequences.<sup>19</sup>

Let us remove now the one-time trading restriction and look for the true subgame perfect equilibrium paths. As shown in the second row of Table 2, the monopsonist is able to only slightly depress the initial price from its competitive level of 0.449 to 0.429 and extend the exhaustion time by only 6 per cent (from 8.0 to 8.5). The monopsonist is clearly better off with the one-time trading restriction because that provides him with the commitment he does not have. As a good indication of this commitment problem, we see that the overall efficiency loss —total cost above those under perfect competition— under full monopsony is only 7 per cent. Moving to the other extreme allocation, it is immediately clear that the monopolist greatly benefits from having removed the one-time trading restriction (since the latter is always available to him). It is more profitably for the monopolist to gradually sell permits to the fringe rather than selling everything at once. Relative to the perfectly competitive solution, we observe a considerable increase in both the initial price and the exhaustion time (55 and 19

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<sup>19</sup>The two solutions do not exactly mirror each other because the price reaction function of the fringe is not linear in the stock, as in the static case.

per cent, respectively). Not surprisingly, this leads to a significant welfare loss of 28 per cent. In sum, dynamics (the opportunity of gradually and frequently come to the market) helps the large seller but severely hurts the buyer.

## 4.2 Collusive Behavior

There is not much to add here to what we already know on collusive behavior except for the case in which there is storability of permits. Two or more sellers of permits could potentially sustain the monopoly path  $p^m$  in Figure 1 only if the cartel persists after  $T^m$ . Then, collusion could in principle be ruled out if the long-run allocations are cost-effective or if the long-run price is fully governed by the price of backstop technologies. Similarly, it is not clear how a large buyer could escape from the Coase conjecture of Figure 2. Unlike the durable-good monopoly, the existence of the backstop (i.e., long-run) price  $\bar{p}$  together with the fact the stocks are in the hands of the fringe rule out the construction of punishment strategies *a la* Ausubel and Deneckere (1987) and Gul (1987) that could support the monopsony path. Fringe's rational expectations do not support a price path that never reaches  $\bar{p}$  but approaches it asymptotically because the latter would require prices to be declining in present value terms.

## 5 AUCTIONING THE PERMITS

So far we have assumed that permits are allocated for free (i.e., grandfathered) to firms. It is true that auctions have been nearly absent from all existing permit markets but recently they have received more attention as an alternative way to allocate permits —perhaps not all but an important fraction of them (e.g., Crampton and Kerr, 2002).<sup>20</sup> One of the strongest arguments in favor of auctioning is its revenue recycling properties, i.e., the possibility of using the auction revenues to reduce distortionary taxation somewhere else in the economy (e.g., Bovenberg and Goulder, 1996). In this section we will stay away from these general equilibrium considerations and we will exclusively focus on strategic manipulation of auction prices. Unlike with the free allocation, an auction scheme has the potential to eliminate manipulation incentives for all firms even when the regulator knows little or nothing about the firms. The regulator's task is then to design the right auction mechanism. The section starts with a theoretical discussion

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<sup>20</sup>In the US sulfur market, for example, less than 3% of the overall allocation is auctioned off every year. Auctions are more common in other resource management problems, e.g., for allocating water rights and fishing quotas (Tietenberg, 2006).

and concludes with a numerical application to water pollution in the Bio-Bio River in southern Chile.

## 5.1 Some Theory

To start, suppose that a total number of permits are to be allocated via a sealed-bid, uniform-price auction in which each firm bids a demand schedule indicating the number of permits willing to purchase at any given price. Note that the uniform-price auction is the closest auction design to the permit markets we have studied so far since all permits are bought at the same price. The problem with uniform-price auctions is that nothing guarantees that firms will reach the perfectly competitive outcome (Milgrom, 2004); although it is one of the multiple equilibria. As first recognized by Wilson (1979) in his pioneer "auctions of shares" article, even when there is a large number of bidders, uniform price auctions can exhibit Nash equilibria with prices far below the competitive price (the price that would prevail if all bidders submit their true demand curves for permits). The reason for this is that uniform pricing creates strong incentives for bidders to (non-cooperatively) shade their bids at the auction in order to depress the price they pay for their inframarginal units.

But if bidders anticipate the perfectly competitive outcome at the uniform-price auction, a large firm may still have incentives to refrain from participating at the auction (i.e., submit an empty schedule) and only trade in the after-auction (i.e., resale) market. Consider Hahn's market structure and let  $P_m(e_m)$  and  $P_f(e_f)$  be the true (inverse) demand curves for permits of the large firm and the fringe, respectively. Note that for convenience in the presentation I have switched from marginal abatement cost curves to demand curves, so  $P_i(e_i) = C'_i(q_i = u_i - e_i)$ .

As depicted in Figure 3, suppose that the regulator's environmental goal is to allocate a total of  $e_0$  permits. To simplify the graphical analysis, suppose further that  $P_m(e_m) = P_f(e_f)$ , which implies that in the absence of regulation unrestricted emissions are  $u_f = u_m = u > e_0/2$ . The aggregate true demand curve is denoted by  $P_{mf}(e_{mf})$ . If all firms were to behave competitively (i.e., bid their true demands), the clearing price of the uniform-price auction would be  $p^*$  and firms will receive  $e_f = e_m = e^*$  permits. These would be firms' emissions as well. There is no reason for after-auction trading since the large firm has exactly its cost-effective allocation. Thus, the large firm's total compliance cost with the regulation would be the sum of two components: abatement costs or profit loss (area under  $P_m(e_m)$  from  $e^*$  to  $u$ ) and permit purchasing costs ( $p^*$  times  $e^*$ ).

But the large firm can do better by bidding an empty demand schedule at the auction and buying permits only in the resale market. Regardless of the price paid by the fringe at the auction —zero if they bid competitively—, the fringe’s supply curve in the resale market is  $S_f(e)$ , that is,  $S_f$  is the price at which the fringe is willing to supply  $e$  permits (or simpler,  $S_f$  is the fringe’s marginal abatement cost curve). The large firm’s optimal permit order is  $e_m < e^*$ , where its marginal purchasing cost is equal to its marginal benefit, i.e.,  $S_f(e_m) + S'_f(e_m)e_m = P_m(e_m)$ . The large firm’s compliance costs has fallen because the increase in abatement costs (area under  $P_m(e_m)$  from  $e_m$  to  $u$ ) is more than offset by the decrease in permit purchasing costs ( $p_m$  times  $e_m$ ). I do not want to insist here on the generality of this result (e.g., what if we have two strategic players?); it seems enough for illustrating that a standard uniform-price auction is unlikely to eliminate incentives for (unilateral) price manipulation (later we will touch on collusion incentives as well).

One radical solution to solve the manipulation problem is to give up the uniform-price format altogether and opt for a discriminatory-price format (e.g., Vickrey, 1961). But if we want to retain the uniform-price format, in part because of its simplicity, Montero (2008) has recently proposed a relatively simple way to fix the problem: allow for rebates or paybacks. Part of the (uniform-price) auction revenues are returned to firms not as lump sum transfers but in a way that firms would have incentives to bid truthfully regardless of their size. More precisely, firms’ final payments (after rebates) are computed following a Vickrey-Clarke-Groves (VCG) principle, that is, making each firm pay exactly for the externality it imposes on the remaining agents.<sup>21</sup> Because of the VCG payoff structure, this new uniform-price auction becomes both ex-post efficient and strategy-proof (i.e., telling the truth is a dominant strategy). Note that since the equilibrium is implemented in dominant strategies, firms and the regulator need know nothing about (other) firms’ characteristics for the scheme to work.

The workings of Montero’s (2008) auction scheme can be easily illustrated with the problem of Figure 3 which I have replicated in Figure 4.<sup>22</sup> It may help to think of the fringe as a single firm, the "fringe firm". The regulator asks each firm  $i = m, f$  to submit a demand schedule,

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<sup>21</sup>A good description of VCG mechanisms can be found in Milgrom (2004).

<sup>22</sup>Note that the auction scheme in Montero (2008) can be easily extended to the case in which the total number of permits to be allocated to firms is endogenous to firms’ bidding schedules and the pollution damage to third parties.

say  $\hat{P}_i(\hat{e}_i)$ , and then clears the auction by allocating  $\hat{e}_i$  permits to firm  $i$  at price

$$\hat{p} = \hat{P}_i(\hat{e}_i) \text{ for all } i$$

where  $\hat{e}_m + \hat{e}_f = e_0$ . To make sure that firm  $i$  bids its true demand curve, its final payment is not  $\hat{p}\hat{e}_i$ , as in a standard uniform-price auction, but  $\hat{p}\hat{e}_i$  minus a rebate specific to  $i$ . The rebate is calculated by constructing a residual supply function for each firm  $i$ , which is obtained by subtracting from the overall supply of permits ( $e_0$  in Figure 4) the sum of the schedules submitted by the remaining firms, so it is independent of firm  $i$ 's bid. For example, if by any reason, the "fringe firm" bids truthfully, i.e.,  $\hat{P}_f(e_f) = P_f(e_f)$ , the large firm's residual supply curve would be  $S_f(e)$  in Figure 4. The residual supply function captures the (marginal) cost to the fringe firm from allocating permits to the large firm (as perceived by the fringe firm). So, if we want the large firm to bid truthfully we must make it bear the full social cost of allocating permits to it. The rebate must be such that the large firm ends up paying exactly this social cost.

Suppose that the large firm does not bid its true demand curve but something higher, say  $\hat{P}_m(e_m) = P_{mf}(e)$  in Figure 4. The auction will clear at  $\hat{p} > p^*$  and the large firm will get  $\hat{e}_m$  permits. The large firm's final payment  $F_m(\hat{e}_m)$  would be the area under  $S_f(e)$  from 0 to  $\hat{e}_m$ , which means that its payback would be the shaded area in the figure, i.e., the difference between the uniform-price payment  $\hat{p}\hat{e}_m$  and the final payment  $F_m(\hat{e}_m)$ . Thus, the large firm's compliance cost when bidding  $\hat{P}_m(e_m) = P_{mf}(e)$  would be  $F_m(\hat{e}_m)$  plus the (true) cost of reducing emissions from  $u$  to  $\hat{e}_m$ . We do not need to extend the analysis here to the case of under-reporting to see that the large firm reaches its lowest compliance cost when it bids its true demand curve, i.e.,  $\hat{P}_m(e_m) = P_m(e_m)$ . In this case the auction will clear at  $p^*$  with a final payment equal the area under  $S_f(e)$  from 0 to  $e^*$ . Regardless of what the fringe firm does, the large firm does best by bidding its true demand curve. Furthermore, the large firm wants to participate at the auction rather than waiting for the resale market.

As formally shown in Montero (2008), the auction mechanism retains its first-best properties even when a group of (or all) firms form a cartel. Since permits are by definition fully transferable in resale markets, cartel firms mimic a single entity at the auction and then proceed with efficient permits transfers among themselves. One of the cartel firms —the serious bidder— submits the cartel true demand curve while the remaining cartel firms submit empty demand schedules. Note that in the perfectly inelastic case of Figure 4, the serious bidder would submit

a lower demand schedule just enough to get the  $e_0$  permits at zero price. But in this particular case under-reporting does not produce any efficiency loss.

Despite being efficient and strategy-proof, the auction mechanism may still face resistance from affected parties since, unlike the free allocation, it leaves rents with the regulator. The auction scheme is, like any other VCG mechanism, a non-budget-balanced mechanism, i.e., we cannot return the totality of the auction revenues to firms without affecting their reporting incentives. In Montero (2008), I propose a partial solution to the problem. Let  $F_j^{-i}(e_j^{-i})$  denote the final payment that firm  $j$  would have hypothetically faced under the same auction scheme but in the absence of firm  $i$ , where  $e_j^{-i}$  is the corresponding number of permits allocated to  $j$ . The regulator can thus fashion a lump-sum additional refunding  $R_i$  for firm  $i$  using these influence-free hypothetical payments. For example,

$$R_i = \frac{1}{n-1} \sum_{j \neq i} F_j^{-i}(e_j^{-i}) \quad (7)$$

This solution assures a perfectly balanced budget (i.e.,  $\sum_{i=1}^n R_i = \sum_{i=1}^n F_i(e_i)$ ) only in the limiting case of a large number of firms. I will now develop a numerical application to further illustrate the workings of the auction scheme including these additional refunding.

## 5.2 An Application to Water Pollution

Beyond solving the price manipulation problem, a well-designed auction scheme may be particularly appealing in environments with few firms and infrequent transactions. Trading water pollution rights is a good example as demonstrated by the disappointing experience in the early 1980s of the Fox River in northern Wisconsin. Despite the supposedly large gains from trading, only a single trade between a municipal wastewater plant and a paper mill has been documented (Tietenberg, 2006).

Our numerical exercise applies to two wastewater treatment plants (Essbio Nacimiento and Essbio Negrete) and three pulp and paper mills (Inforsa, Forestal Santa Fe and Celpac Mininco) discharging biochemical oxygen demand (BOD) along an 18 kilometers section of the Bio-Bio River in southern Chile. Following Saavedra (2002), the regulator's objective is to maintain the level of dissolved oxygen (DO) in the river equal or above 8.35 mg/lts at some chosen control point, which is located 18 kms downstream from the furthest away source. Table 3 summarizes firms' characteristics:  $d_i$  is the distance between source  $i$  and the control point,  $q_i^0$  is  $i$ 's waste

mass discharge in the absence of regulation in kg/day,  $v_i$  is the flow of water carrying the waste in  $\text{m}^3/\text{sec}$ , the ratio  $q_i^0/v_i$  is unrestricted BOD discharge in mg/lts, and  $P_i(q_i)$  is firm  $i$ 's demand for mass discharges at its location (i.e., marginal abatement cost). As explained by Saavedra (2002), a firm can reduce its BOD only by reducing its mass discharge  $q_i$ , not by increasing its flow  $v_i$ , which is already at its maximum level.<sup>23</sup>

I calculate the impact of individual discharges on DO at the control point with a simple linear model, which is

$$DO = DO^0 - A \sum_{i=1}^5 \frac{q_i}{v_i d_i}$$

where  $DO^0$  is the DO level in the absence of any BOD discharges (9 mg/lts) and  $A$  is a conversion factor (9.4866). In the absence of regulation, the level of DO at the control point would fall to 5.27 mg/lts, way below the 8.35 mark. A traditional approach for the regulator to reach its DO goal is to impose a uniform BOD standard of 35 mg/lts.<sup>24</sup> As shown in Table 4, total compliance costs under this command-and-control (CAC) approach would be 11.7 million dollars per year. Since firms are heterogeneous in terms of location  $d$  and water flow  $v$ , it is not immediately obvious from looking at the diverging marginal costs faced by each firm, i.e.,  $P_i(q_i)$ , to see how cost-effective or ineffective this CAC approach is.

Since the regulator does not know firms' demand curves, he cannot implement the cost-effective solution by imposing different BOD standards on firms.<sup>25</sup> But the VCG auction scheme proposed in Montero (2008) does precisely that in a decentralized manner and in dominant strategies. The results are summarized in Table 5. Total compliance costs under the auction scheme are 6.2 million dollars: 3.8 millions coming from abatement costs —only 32% of the CAC cost— and 2.5 millions from permit purchasing costs. From looking at the difference between the uniform-price payments ( $p_i q_i$ ) and the final payments ( $F_i$ ), we see that paybacks vary widely from 38 dollars in the case of Essbio Negrete to 577,913 dollars in the case of Inforsa. Essbio Negrete is the smallest source so it faces an almost perfectly elastic residual supply curve while Inforsa faces a much less elastic residual supply curve. Interestingly, this latter firm is the only one that sees its compliance costs increase when moving from CAC to

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<sup>23</sup>To work with interior solutions I let demand curves to be perfectly inelastic at  $q_i = 0.05q_i^0$ . In other words, it becomes prohibitively costly to reduce beyond 95%.

<sup>24</sup>In fact, the 8.35 mg/lts goal was obtained from requiring each source to discharge no more than 35 mg/lts of BOD; which is the standard authorities have previously used to regulate pollution in other rivers in the country.

<sup>25</sup>Even if the regulator had a good idea of firms' marginal cost curves, it would be politically impossible to imagine a regulator with the discretion to impose different standards across sources based on his information on marginal costs.

the auction scheme.

We can now use the lump-sum refundings,  $R_i$ , of expression (7) to reduce firms' compliance costs even further. As shown in the last column of Table 5, with this additional refunding total permit purchasing costs have decreased to just 10 percent of total abatement costs; almost replicating a cost-effective free allocation of permits. And as with any free allocation of permits, it is not surprising that some sources may end-up profiting from the regulation.<sup>26</sup>

## 6 SOME EMPIRICAL EVIDENCE

There are several grandfathering permit markets in which market power has never been an issue; for example, the U.S. EPA trading program initiated in the 1980s (Tietenberg, 1985 and 2006), the Santiago's particulate market (Montero et al., 2002) and the E.U. emissions trading system (Ellerman and Joskow, 2008). The first instance of a permits market in which all of the permits are auctioned off has recently taken off in the U.S. Northeast under the Regional Greenhouse Gas Initiative (RGGI). The auction format adopted by RGGI is a sealed-bid, uniform-price. All four auctions that have been conducted so far have cleared at relatively low prices. For example, the last auction, held on June 17, 2009, cleared at \$3.23 for 2009 vintage allowances. According to Potomac Economics, a consultant, these low prices reflect supply and demand fundamentals (i.e., low-binding cap) and not collusion or manipulation by bidders.<sup>27</sup> While it is difficult to think of collusion with more than 50 bidders (although 56% of the allowances went to just 4 bidders), we cannot just rule out the possibility of unilateral manipulation *a la* Wilson (1979).<sup>28</sup>

There are two existing (grandfathering) programs for which there is more detailed analysis and data to take a closer look at the problem; these are the U.S. sulfur market and the Southern California NO<sub>x</sub> market. Let us look at the sulfur market first. With entirely different methodologies, the works of Ellerman and Montero (2007) and Liski and Montero (2009a) offer

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<sup>26</sup>Note also that Inforsa is still worse off with the move from CAC to the auction scheme; but in the absence of complete information about other firms' characteristics no firm can anticipate that so as to oppose the regulatory move.

<sup>27</sup>See [http://www.rggi.org/docs/Auction\\_4\\_News\\_Release\\_MM\\_Report.pdf](http://www.rggi.org/docs/Auction_4_News_Release_MM_Report.pdf)

<sup>28</sup>The market for trading summer NO<sub>x</sub> permits in the Northeast region of the US —known as the Ozone Transport Commission (OTC) market— is also an interesting case. Although there is no evidence of market power in the OTC market itself, Mansur (2007) explains that some electric companies that trade in the OTC market do have market power in their (restructured) energy markets. And since pollution intensity varies across plants, this market power has had an effect on the performance of the OTC market in terms of clearing prices and cost-effectiveness.

no indication of market power, at least in the form considered in this paper. Using aggregate data from 1995 through 2003, Ellerman and Montero (2007) find that the actual emissions path is reasonably close to a simulated path of perfect competition. In the static setting of Hahn, total emissions provide no information on the extent of market power (obviously, individual emissions do). But in the dynamic setting of the sulfur market, any indication of market power must show up in a distorted emissions path, as discussed in Section 4.

Liski and Montero (2009a), on the other hand, use publicly available data on emissions and permit allocations to track down the actual compliance paths of the four largest players in the market, which together account for 43% of the permits allocated during the generous-allocation years of the program, i.e., 1995-1999. The fact that these players, taken either individually or as a cohesive group, appear as heavy buyers of permits during and after 2000, practically rules out, according to their theory (see Section 4), market power coming from the initial allocations of permits. They further comment on a second piece of evidence, based on trading activity, that reinforces their finding that market power is less of a problem in the sulfur market. According to their theory, a large agent exercising buyer-power will never sell permits in the market because this would only move forward the arrival of the long-run equilibrium. They explain, however, that the EPA allowance tracking system shows significant sales by the large buyers.<sup>29</sup>

Note however, that neither of these two studies constitute a formal test of market power (a test comparing prices and marginal abatement costs). It is certainly an interesting area for future research estimating marginal cost curves from publicly available data such as prices and emissions and then comparing those cost figures to actual prices. Finding evidence of market power (i.e., departure from marginal cost pricing) under such a test would open up an entirely new set of theoretical questions as to what could explain the presence of market power beyond that attributed to the initial allocation of permits.

The California NO<sub>x</sub> market provides less conclusive evidence. Taking advantage of the intertemporal linkages in its design, Holland and Moore (2008) test whether the theoretical predictions of a perfectly competitive model are consistent with the actual data on permits and emissions. They verify that facilities do trade intertemporally as permitted by two overlapping cycles of permits; the pattern of permits use, however, is not entirely consistent with their predictions. For example, they find some facilities holding too many permits. The authors do

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<sup>29</sup>They indicate that by the end of year 2000, American Electric Power had sold about 1.1 million of current-vintage allowances and Southern Company about 1.5 million.

not go on explaining what could be causing the discrepancy between theory and actual data; so I can only speculate that market power may have something to do with it.

Kolstad and Wolak (2008) also look at the NOx market but from a different angle. Nearly 25% of the NOx permits were allocated to facilities that sell power into the California electricity market, which has been recognized for its (unilateral) market power problems, particularly during the summer of 2000 (e.g., Borenstein et al. 2002; Joskow and Kahn, 2002). Kolstad and Wolak (2008) explore the extent to which electric utilities used the NOx market to enhance their ability to exercise (unilateral) market power in the electricity market. They find that above average NOx permit prices during 2000 and 2001 were primarily used by electricity generators to cost-justify higher bids into the electricity market that would set higher prices for all electricity they produced. Given the fact that electricity was historically regulated, privately owned generators may have inferred that they could be required to "cost justify" their bids ex post to a regulator. In a NOx market of ample price dispersion,<sup>30</sup> it seems then that generators were purposefully looking for higher NOx prices that could be uncontestedly passed onto electricity prices. But if this is the case, the following question remains: how could a generator justify to be systematically at the higher end of the price range?

There is an alternative explanation that one could put forward. In a world where prices do not follow the law of one price, as in the sulfur market (Joskow et al., 2008), but rather they are the result of bilateral transactions, it is possible to think that in their rush to deliver electricity at high prices, generators had a lower bargaining power than permit buyers in other industries. This explanation, however, would not be entirely consistent with the authors' finding that changes in NOx prices do not affect generators' bidding behavior in the same way as do changes in other fuel prices. In any case, the kind of permit market manipulation advanced by Kolstad and Wolak (2008) is unrelated to the raising rival's cost strategy discussed in Section 3. It does not even require firms to be large in the permits market. It requires a thin permit market with poor arbitrage conditions and firms subject to some sort of regulatory oversight that prevents them to bid freely in the output market. All this makes the case very specific to California.

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<sup>30</sup>Year 2000 witnessed a significant increase in the standard deviation of transaction prices for 2000 and 2001 vintage permits.

## 7 FINAL REMARKS

I have reviewed the literature on market power in pollution permit trading and contributed with some new results and ideas. It seems that our good understanding in the case of a dominant (or strategic) agent playing against a fringe of polluting agents it is not easily exportable to the case of multiple strategic agents. Some of the approaches being proposed are not entirely satisfactory in part because of the multiplicity of equilibria. It also seems difficult to come up with general theoretical predictions on how imperfectly competitive permits and output markets interact; they depend to a large extent on the specifics of each case. When we move to dynamic markets in which firms build up and exhaust stocks of (storable) permits, we find an important asymmetry not present in the static case. A large buyer of permits has great difficulties in exercising market power because of a commitment problem, very much like the durable-good monopoly. Conversely, a large seller uses the market dynamics to extend its market power by following a more gradual selling path. In moving from grandfather allocations to auction allocations, properly designed auction schemes can greatly alleviate market power problems as long as they create incentives for wide participation and truthful bidding. Finally, an empirical revision of the functioning of past and existing permit markets shows no indication of market power that can be of concern.

Let me offer a few concluding thoughts on related topics not covered by the paper. There are other environmental markets that may share some of the properties of the pollution markets reviewed here. Amundsen and Nese (2004), for example, discuss how the interaction of an imperfectly competitive market of green certificates (GC) with an imperfectly competitive electricity market can produce unexpected outcomes like fixed GC prices. Based on this results, the authors argue the GC market may well be replaced by a plain subsidy for green power. I am curious if any of the results of Amundsen and Nese (2004) can be applied to pollution markets (that interact with output markets).

In addition, the paper has been developed as if all transactions occurs in spot markets. In view of the different type of market transactions that we observe in more recent permit markets, it is natural to ask whether and how our analysis would change if we extended the scope of the market to cover forward transactions. The demand for forward transactions typically arises due to the need to share risk among market participants, but it is well known that oligopolistic firms can also choose to enter the forward market due to strategic reasons (Allaz and Vila, 1993). Forward contracting of production provides a commitment to a future market share, but

leads to a prisoners' dilemma type of situation where firms end up behaving more competitively than without forward markets. Liski and Montero (2006), however, show that the existence of forward markets increases the scope for collusive outcomes in an oligopolistic setting (i.e., two or more large firms), if the traded good is reproducible and interaction is repeated over time.

Finally, the paper is also silent in comparing the permit trading instrument to alternative instruments such as taxes in the presence of imperfectly competitive markets and imperfectly informed regulators. If the regulator were to use the linear instruments of Weitzman (1974), i.e., plain free allocated permits and linear taxes, the answer is quite obvious. The price instrument is superior to the quantity instrument because it does not give up its cost-effectiveness. But this advantage can be eliminated if permits are auctioned off in a cost-effective manner, that is, in a manner that firms bid truthfully.

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Figure 1. Equilibrium price path for a large seller of storable permits

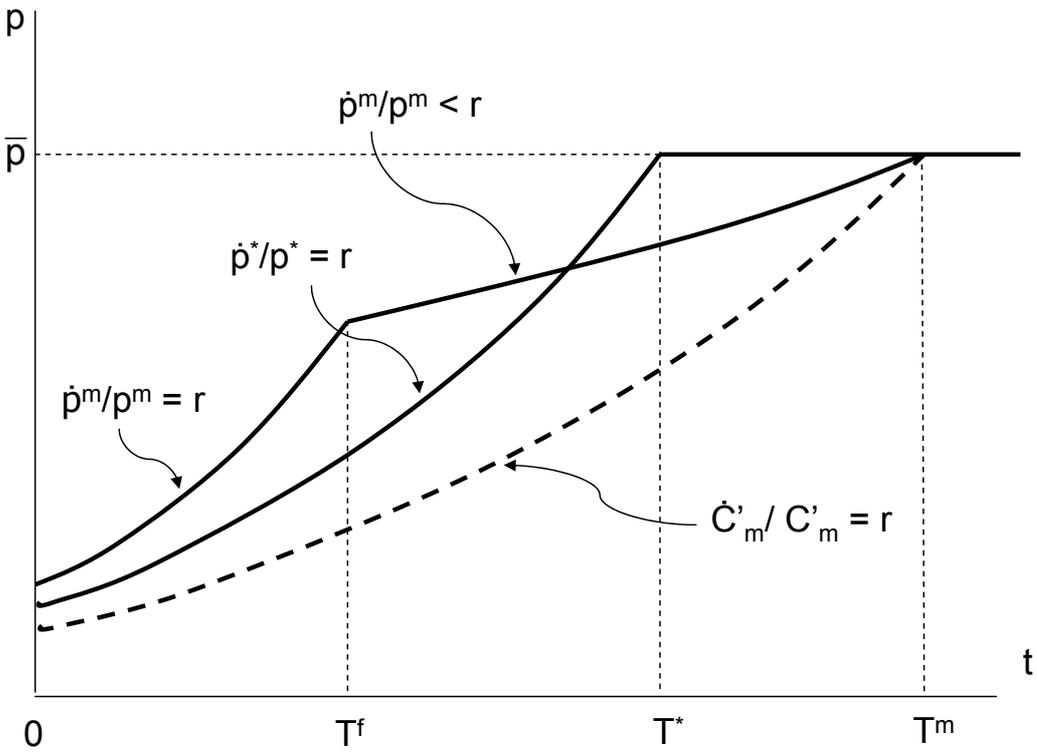


Figure 2. Time-consistency problem for a buyer of permits

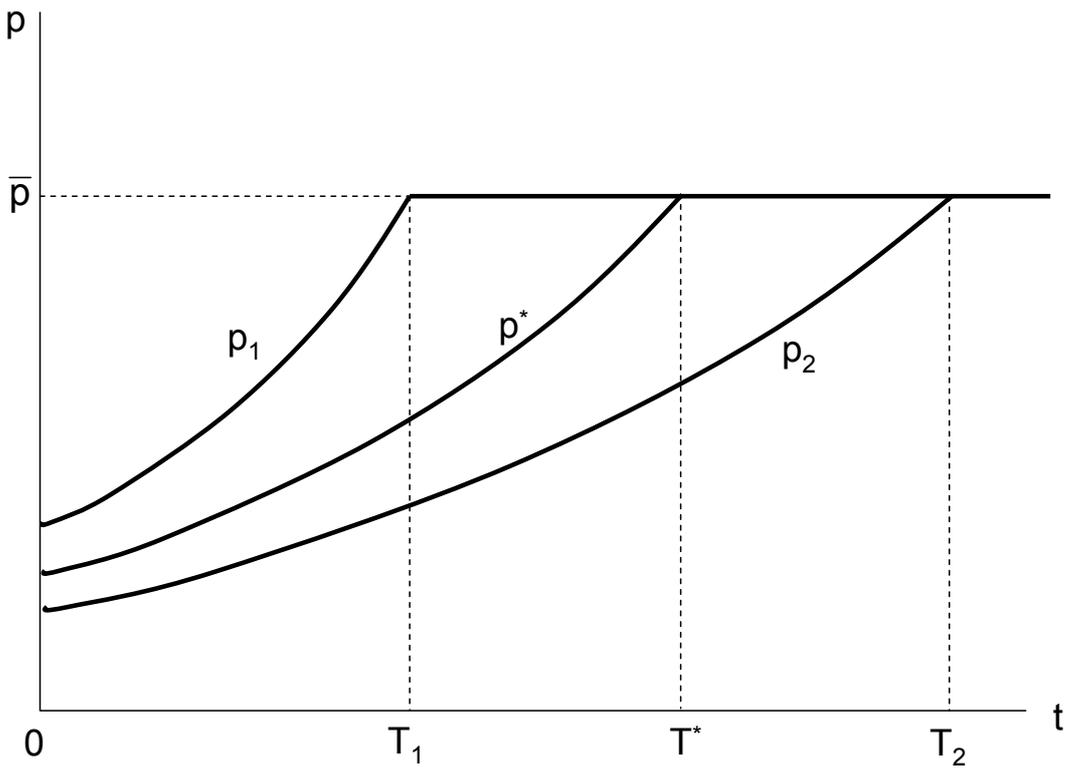


Figure 3. A large firm that disregards the auction

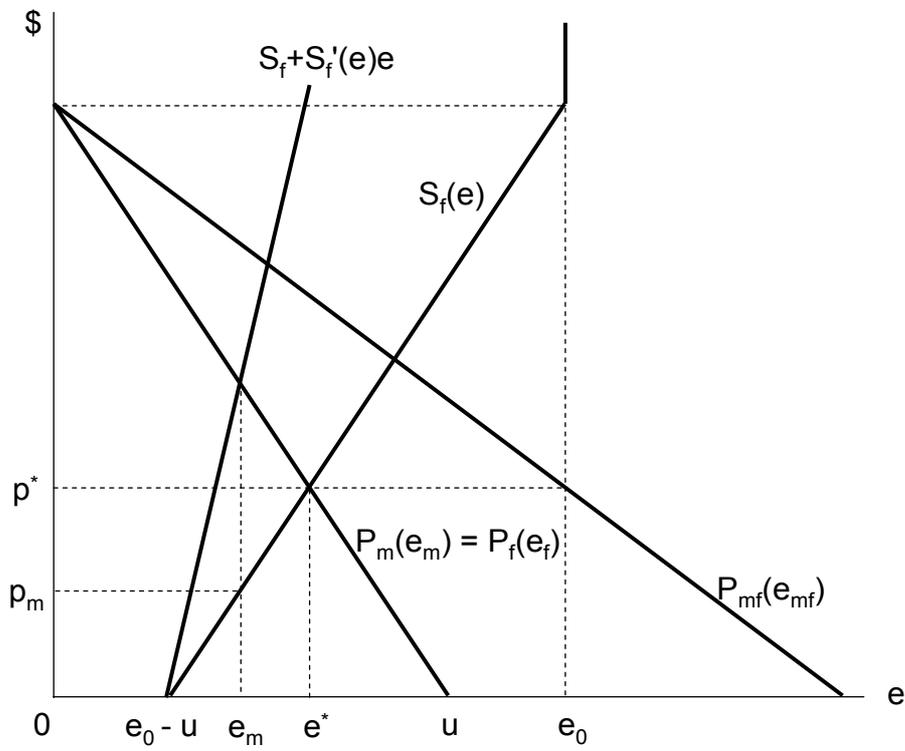


Figure 4. A large firm that bids truthfully

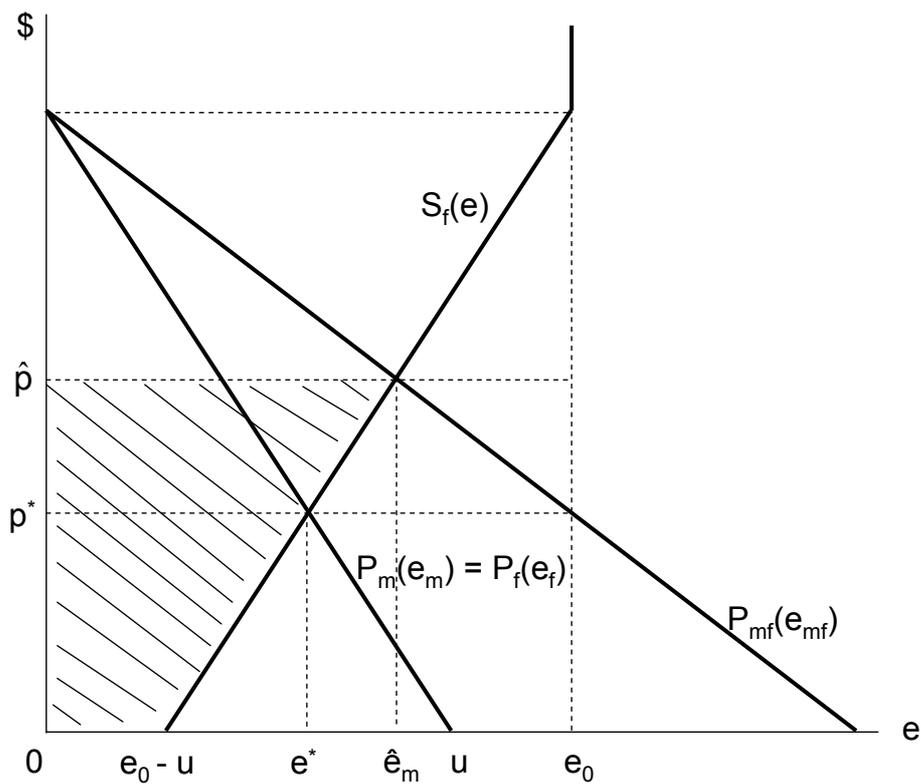


Table 1. Permit Trading with Perfect and Imperfect Output Competition

	$a_m = 1$ $a_f = 1$		$a_m = 1.5$ $a_f = 0.5$		$a_m = 0.5$ $a_f = 1.5$	
	PCO/MPP	MPO/MPP	PCO/MPP	MPO/MPP	PCO/MPP	MPO/MPP
$y_m$	2	1.714	2.083	1.787	1.917	1.642
$y_f$	2	2.057	1.917	1.975	2.083	2.140
$q_m$	1	0.714	0.917	0.617	1.083	0.811
$q_f$	1	1.057	1.083	1.144	0.917	0.970
$x_m$	0	0	0.333	0.333	-0.333	-0.333
$p$	2	2.114	2.167	2.289	1.833	1.940
$R$	6	6.229	6	6.238	6	6.219

Notes: PCO = perfect competition in the output market; MPP = market power in the permits market; MPO = market power in the output market.

Table 2. Subgame Perfect Monopsony and Monopoly Solutions

Equilibrium Path	Initial Price	Terminal Time	Welfare Loss
Perfectly Competitive	0.449	8.0	0
Monopsony	0.429	8.5	7%
Monopoly	0.694	9.5	28%

Table 3. Firms' Characteristics

Source's name	$d_i$ kms	$q_i^0$ kg/day	$v_i$ m <sup>3</sup> /day	$BOD^0 = q_i^0/v_i$ mg/lts	$P_i(q_i)$ \$/kg/day
Essbio Nacimiento	1.1	1,069	5,873	182	$83.4 - 0.0780q$
Inforsa	1.4	7,714	31,104	248	$1248.2 - 0.1618q$
Forestal Santa Fe	4.5	10,977	69,915	157	$866.3 - 0.0789q$
Celpac Mininco	17.7	4,873	46,855	104	$4863.9 - 0.9981q$
Essbio Negrete	18.0	350	1,923	182	$154.6 - 0.4418q$

Source: Saavedra (2002). Definition of variables in the text

Table 4. Costs and Allocations under a Uniform BOD Standard

Source's name	$BOD = q_i/v_i$ mg/lts	$P_i(q_i)$ \$/kg/day	abat. cost \$/year
Essbio Nacimiento	35	67.4	29,075
Inforsa	35	1072.1	3,551,379
Forestal Santa Fe	35	673.1	2,870,937
Celpac Mininco	35	3226.0	5,216,527
Essbio Negrete	35	124.9	17,654
Total			11,685,572

Table 5. Costs and Allocations under the Auction Scheme

Source's name	$q_i$ kg/day	BOD mg/lts	$p_i = P_i(q_i)$ \$/permit	abat. cost \$/year	$p_i \cdot q_i$ \$/year	$F_i$ \$/year	$F_i - R_i$ \$/year
Essbio Nacimiento	53	9	7,225	40,221	386,194	376,093	-135,225
Inforsa	1,089	35	1,072	3,550,539	1,167,786	589,873	584,389
Forestal Santa Fe	9,097	130	148	139,498	1,349,591	1,221,393	830,030
Celpac Mininco	4,817	103	56	1,589	271,091	266,112	-298,731
Essbio Negrete	18	9	1,349	24,422	23,599	23,561	-590,680
Total				3,756,270	3,198,261	2,477,033	389,784