OPTIMAL POLICY WITH TRADABLE AND BANKABLE POLLUTION PERMITS: TAKING THE MARKET MICROSTRUCTURE INTO ACCOUNT

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Abstract

This paper analyzes how the way emission permits are traded—their market microstructure—affects the optimal policy to be adopted by the environmental agency. The microstructure used is one of a *quote driven market* type, which characterizes many financial markets. Market makers act as intermediaries for trading the permits by setting an ask price and a bid price. The possibility of bank permits is also introduced in our dynamic two-period model. We consider two models whether the market makers are perfectly informed about the technology of the producers or not. When the market makers have complete information, the equilibrium price of permits is the same as if the market is walrasian. When they are imperfectly informed, they may set a positive spread between bid and ask permit prices, which creates some inefficiency as the marginal abatement costs of polluters do not equalize. By allowing more flexibility in the use of the permits, banking may reduce the spread. Moreover, it may introduce price rigidities due to intertemporal arbitrage. In this framework, the circumstances under which banking should be allowed or not depend crucially on the evolution of the marginal willingness to pay for the environment.

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1. Introduction

Following Dales (1968), Montgomery (1972) shows that a market for pollution permits is an efficient instrument to reach an environmental target, provided that the market is competitive. Several authors have relaxed this latter assumption. For instance, Hahn (1984) looks at market power and Stavins (1995) analyzes the effect of different kinds of transaction costs. They both emphasize the impact of the initial permit allocation among firms on the efficiency properties of the instrument.

Another interesting issue that has not been considered much in the literature is how trades in permits do actually take place on large markets such as the US *Acid Rain Program* or the forthcoming world markets in greenhouse gases emission permits. This issue is crucial for understanding the functioning of such markets and its impact, if any, on the optimal environmental policy. The analysis of these markets shows that their microstructure is—or is likely to be—close to those which rule financial markets, as suggested by the involvement of brokerage firms in trading SO_2 and NO_x allowances[1] and the increasing interest of international exchanges in the development of greenhouse gas permits markets.[2] Indeed, pollution permits share many characteristics of financial assets. They are perfect substitutes, their transport and inventory are not costly and derivatives may easily be developed.

In this respect, Germain, Lovo, and van Steenberghe (2000) make a link between environmental and financial economics. Taking an allocation of pollution permits among firms as given, they investigate the effect of a financial-type market microstructure for these permits, on the total number of permits to be allocated by the environmental agency. The microstructure used is of a *quote driven market* type. Market makers act as intermediaries for trading the permits by setting an ask price (i.e., a price at which they are ready to sell permits) and a bid price (i.e., a price at which they are ready to buy permits), the former being larger than or equal to the latter. Market makers may then diffuse their prices either through informal channels, for instance, by phone or via Internet, or in organized exchanges.[3]

Since the model developed by Germain, Lovo, and van Steenberghe (2000) is static, market markers facing uncertainty may be left with unsold permits in some states of the world, which leads them to set a spread between bid and ask prices. The aim of the present paper is to extend this analysis into a dynamic setting. The motivation is twofold. First, the dynamic setting allows

[1]See, among others, Natsource, Cantor Fitzgerld EBS, and Evolution Markets.

[2]See, for instance, the Australian Stock Exchange, the New Zealand Options and Futures Exchange, the International Petroleum Exchange, and the Chicago Board of Trade.

[3]A detailed presentation of financial quote driven markets is provided in the survey of Biais (1990) and in the books by Biais et al. (1997) and O'Hara (1995).

to solve (part of) the uncertainty (incomplete information) faced by the environmental agency and by market makers. Second, we introduce a system of intertemporal trading where permits may be banked but not borrowed. This is an important feature of existing and envisioned pollution permits markets. Banking would allow a less wasteful use of permits. Those which have not been sold by the market makers could then be used in subsequent periods.

Dynamic models with tradable pollution permits have recently received much attention. Cronshaw and Kruse (1996) and Rubin (1996) extend the work of Montgomery (1972) and show that banking can decrease the total costs of achieving a fixed emission target over all periods. However, when banking takes place, the levels of ambient pollution do not necessarily correspond to those specified by the total amount of permits distributed. While Kling and Rubin (1997) have shown that this leads the economy to a state which is not always socially efficient, Requate (1998) points out that allowing banking under uncertainty can improve welfare in some situations. Finally, Phaneuf and Requate (2002) argue that banking may distort firm's incentives to invest in cleaner technology.[4]

We work in a discrete-time two-period model. As intermediary results, we reach similar conclusions to those of Requate (1998), but in a slightly different context. Rather than investigating the effect of demand uncertainty on the output of the polluters, we focus on the incomplete information about the production functions that is faced by the environmental agency and by market makers. Although both settings lead to uncertain aggregate demand and supply of permits, our setting implies that agents learn the production functions by observing trades in permits in the first period and do not face any uncertainty in the second period.[5]

The structure of the paper is as follows. In the next section we introduce the model. We analyze the optimal policy to be implemented by the environmental agency when the emission permits are traded in the framework of a quote driven market microstructure. In Section 3, we assume that the market makers are perfectly informed about the technology of the firms. The price of permits then forms like on a walrasian market. In Section 4, market makers are assumed to be imperfectly informed about the technology of the firms. Then a spread may appear between the bid and ask prices that are set by the market makers. For each of the two models considered in Sections 3 and 4, one considers under which circumstances bank-

[4]Also see the interesting paper of Hagem and Westskog (1998), dealing with market power, banking and borrowing in a world with certainty, as well as Schennach (2000) who looks at the effects of technological innovations, growth in electricity demand, or changes in environmental regulations under uncertainty.

[5]We depart from the dynamic model of Yates and Cronshaw (2001), where the agency commits to a permit policy for the two periods. Another difference with our framework is that these authors allow for full intertemporal trades (banking and borrowing).

ing should be recommended. Finally, Section 5 summarizes the results and concludes.

2. The Model

As mentioned above, the aim of the analysis is to introduce a microstructure for a pollution permits market in a dynamic context. To that purpose, time is divided into two periods ($t = \{1, 2\}$). There are three types of agents: firms that produce and pollute, market makers who compete on the permits market, and the environmental agency that chooses the amount of permits to be distributed so as to maximize social utility.

In each period, the environmental agency defines a certain amount of permits to be distributed to the firms according to an exogenous sharing rule. The firms are not allowed to emit more pollutants than the amount of permits in their possession in each period. However, banking of permits is allowed, i.e., permits which have been distributed but not used in the first period are valid in the second period.

There is a continuum of firms, each firm being characterized by an exogenous productivity parameter m with $0 \leq m \leq \bar{m}$. Denoting by $n(m)$ the number of firms characterized by m, the total amount of firms is $N = \int_0^{\bar{m}} n(m)\,dm$. Without loss of generality, we set $N = 1$.

The production function of a firm characterized by m writes

$$y_t = kmg(x_t), \tag{1}$$

where y_t is the output of a firm in period t, x_t is its amount of emissions in the same period, and k is a positive exogenous random parameter, whose density function is $f(k)$ defined on the domain $[\underline{k}, \bar{k}]$. $g(.)$ is strictly concave and differentiable, with $\gamma(x_t) \equiv \frac{dg}{dx_t} > 0$ and $g(0) = 0$. As k does not depend on m, one assumes that all firms are randomly affected in the same multiplicative way. This specification avoids any curvature effects in that it amounts to a single shift of the production function and is at the same time tractable.

The total amount of pollutants emitted in period t is then

$$z_t = \int_0^{\bar{m}} x_t(m)\,n(m)\,dm. \tag{2}$$

Pollution causes damages that we assume to be linear in the emissions:

$$\Omega_t(z_t) = \pi_t z_t, \tag{3}$$

where π_t may be interpreted as the social marginal willingness to pay for a reduction in the stock of pollutants.[6]

[6]As damages are a function of current pollution, the pollutant is called a *flow pollutant*, as opposed to a *stock pollutant* when pollution accumulates. However, our framework extends immediately to stock pollution when the pollutant accumulates linearly and when damages are linear.

Finally, the total production in period t is

$$Y_t = \int_0^{\bar{m}} kmg(x_t(m))\, n(m)\, dm. \tag{4}$$

The sequence of decisions is as follows. At the beginning of each period t, the environmental agency defines a certain amount of permits $\bar{z}_t$ and allocates them to the firms according to a given sharing rule. For the sake of simplicity, we choose the egalitarian sharing rule, where each firm receives the same quantity of permits $\bar{z}_t$ in period t.[7] Note that our results are robust to this simplifying assumption. What matters is that the chosen allocation rule leads to at least some trades in permits.[8]

Assumed to be price-takers, firms maximize their profits and trade permits among each other and with the market makers. Each agent takes into account the impact of his decision on the subsequent decisions. In particular, the agency takes the firms and the market makers' behavior into account when defining the amount of permits. This two-period model is thus solved by backward induction: (i) firms maximize their profits in period $t = 2$; (ii) market makers set their bid and ask prices in period $t = 2$; (iii) the agency computes the amount of permits to be distributed in period $t = 2$. Then this sequence of operations is repeated for $t = 1$.

At the beginning of the first period, when the agency sets $\bar{z}_1$, the random event has not yet occurred so that the parameter k is unknown. We however assume that the agency knows the density function $f(k)$. The random event occurs during period 1, after the setting of $\bar{z}_1$, but before firms trade permits. The latter are thus supposed to know the true value of k when they trade permits. As far as the market makers are concerned, we will study two alternative hypotheses, whether they know the parameter k or only its density function. We do so in order to highlight the impact of asymmetric information on the equilibrium of the permits market and on the environmental policy.

In the second period, the environmental agency has learned the value of k by observing either the volume of trades in permits or the aggregate level of production in the first period. This applies also to the markets makers when it is assumed that they do not know k in period 1.

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[7]As the number of firms has been normalized to 1, $\bar{z}_t$ is also the total amount of permits distributed.

[8]In fact, aggregate demand and supply come from differences, for each firm, between their initial allocation of permits and their need of emission permits. What matters in our analysis is only that these differences vary across firms in order to have trades. The fact that these differences come from different production functions or from different allocations is not important for the rest of the analysis. Also note that the only rule leading to no trades in permits would consist in allocating permits in such a way that the marginal productivity of emissions is equalized accross firms. In that case, the analysis of the microstructure for emission permits becomes irrelevant.

We now introduce a market for pollution permits. We focus on a microstructure of a quote driven type, starting with the case in which the market makers know the true value of the parameter k.

3. Market Makers Perfectly Informed

3.1. The Last Period

Recall that the parameter k is known by all agents in the second period.

3.1.1. The Firm

In the second period, each firm solves

$$\max_{\{x_2^f \geq 0\}} kmg(x_2) - a_2 \max\left\{x_2 - \bar{z}_2 - B^f, 0\right\} + b_2 \max\left\{\bar{z}_2 + B^f - x_2, 0\right\}, \quad (5)$$

where the ask (bid) price considered, $a_2(b_2)$, is the lowest (highest) of each market maker's ask (bid) price, that is,

$$a_2 = \min\left\{a_2^1, a_2^2\right\} \text{ and } b_2 = \max\left\{b_2^1, b_2^2\right\} \quad (6)$$

and where $B^f (0 \leq B^f \leq \bar{z}_1)$ is the amount of permits that have been banked by the firm from the first period. Let $\eta(\cdot) \equiv \gamma^{-1}(\cdot)$ with η decreasing as g is concave. Then its level of emissions is given by

$$x_2 = \left\{\begin{array}{lll} \eta\left(\dfrac{a_2}{km}\right) & \text{if} & \eta\left(\dfrac{a_2}{km}\right) - \bar{z}_2 - B^f > 0 \\ \bar{z}_2 + B^f & \text{if} & \eta\left(\dfrac{a_2}{km}\right) \leq \bar{z}_2 - B^f \leq \eta\left(\dfrac{b_2}{km}\right) \\ \eta\left(\dfrac{b_2}{km}\right) & \text{if} & \eta\left(\dfrac{b_2}{km}\right) - \bar{z}_2 - B^f < 0 \end{array}\right\}. \quad (7)$$

Since firms are characterized by different values of the parameter m, their net demand differs and gains from trading permits occur. The higher m, the higher the emissions of the firm and the higher its net demand.

3.1.2. The Market Makers

We now introduce a microstructure characterized by the presence of market makers who compete "à la Bertrand" by setting bid and ask prices in each period. Without the loss of generality, we assume that only two market makers—indexed by j—compete. In each period, each market maker j sets its bid price b_t^j—the price at which he is ready to buy permits—and its ask price a_t^j, the price at which he is ready to sell permits. Consider for a moment that firms either have no incentives to bank permits or are indifferent between to bank and not to bank. This statement will be proved below in Proposition 2 (Section 3.2.1). Assuming that firms do not bank any permits when they are indifferent between doing so or not, we may set $B^f = 0$ for all firms.

In this case, the aggregate demand and supply of permits by firms are, respectively,

$$D_2(a_2, k) = \int_{\frac{a_2}{k\gamma(\bar{z}_2)}}^{\bar{m}} \left[\eta\left(\frac{a_2}{km}\right) - \bar{z}_2\right] n(m)\, dm \tag{8}$$

and

$$S_2(b_2, k) = \int_0^{\frac{b_2}{k\gamma(\bar{z}_2)}} \left[\bar{z}_2 - \eta\left(\frac{b_2}{km}\right)\right] n(m)\, dm. \tag{9}$$

Each market maker maximizes its profit under the constraint that he cannot sell more permits than the sum of those he buys and those he has banked (B^j) from the first period. Therefore, each of them chooses $\{a_2^j, b_2^j\}$ in order to solve

$$\max_{\{a_2^j, b_2^j\}} \Pi_2^j = a_2^j D_2^j\left(a_2^j, a_2^{3-j}, k\right) - b_2^j S_2^j\left(b_2^j, b_2^{3-j}, k\right) \tag{10}$$

subject to

$$D_2^j\left(a_2^j, a_2^{3-j}, k\right) = S_2^j\left(b_2^j, b_2^{3-j}, k\right) + B^j(k) \tag{11}$$

and

$$a_2^j \geq b_2^j \tag{12}$$

with

$$D_2^j\left(a_2^j, a_2^{3-j}, k\right) = D_2\left(a_2^j, k\right) 1_{\{a_2^j < a_2^{3-j}\}} \tag{13}$$

$$S_2^j\left(b_2^j, b_2^{3-j}, k\right) = S_2\left(b_2^j, k\right) 1_{\{b_2^j > b_2^{3-j}\}}, \tag{14}$$

where $1_{\{.\}}$ is the indicator function: $1_{\{x<y\}} = \left\{\begin{smallmatrix} 1 & \text{if } x<y \\ 0 & \text{otherwise} \end{smallmatrix}\right\}$, and $\{a_2^{3-j}, b_2^{3-j}\}$ given.

PROPOSITION 1: *In the second period, an equilibrium is reached when the market makers choose* $a_2^1 = a_2^2 = b_2^1 = b_2^2 = \sigma_2$*; they enjoy a positive profit* $\Pi_2^j = \sigma_2 B^j \geq 0$ *for* $j = 1, 2$.

Proof: This follows from a standard Bertrand competition analysis. ■

As there is no spread, the market clearing condition takes the following form:

$$ED_2(\sigma_2, k) = B^J(k), \tag{15}$$

where $ED_2(\sigma_2, k)$ is the aggregate excess demand of firms and $B^J =_{def} \sum_{j=1}^{2} B^j$. Given (8) and (9), (15) may then be written as

$$\int_0^{\bar{m}} \eta\left(\frac{\sigma_2}{km}\right) n(m)\, dm = \bar{z}_2 + B^J, \tag{16}$$

which implicitly gives σ_2 as a function of k, $\bar{z}_2$, and B^J.

Given the previous equation, it appears that the Bertrand competition between perfectly informed market makers leads to the walrasian market solution.

3.1.3. The Agency

Knowing the behavior of the firms and the market equilibrium condition, the environmental agency defines the amount of permits $\bar{z}_2$ to be distributed in the second period. It maximizes the social utility of period 2, i.e.,

$$\max_{\{\bar{z}_2\}} U_2 \equiv Y_2 - \pi_2 z_2 \tag{17}$$

subject to the market clearing condition (16) and where the aggregate production is given by

$$Y_2 = \int_0^{\bar{m}} kmg\left(\eta\left(\frac{\sigma_2}{km}\right)\right) n(m)\, dm, \tag{18}$$

and the aggregate emissions are

$$z_2 = \int_0^{\bar{m}} \eta\left(\frac{\sigma_2}{km}\right) n(m)\, dm. \tag{19}$$

The first-order condition of this problem leads to

$$\int_0^{\bar{m}} [\sigma_2 - \pi_2]\eta'\left(\frac{\sigma_2}{km}\right) \frac{d\sigma_2}{d\bar{z}_2} \frac{n(m)}{km}\, dm = 0,$$

which leads to

$$\sigma_2 = \pi_2 \tag{20}$$

because the function under the integral is of constant sign ($\eta' < 0$ and $\frac{d\sigma_2}{d\bar{z}_2} < 0$ by (16)). Accordingly, the environmental agency chooses

$$\bar{z}_2 = \int_0^{\bar{m}} \eta\left(\frac{\pi_2}{km}\right) n(m)\, dm - B^J. \tag{21}$$

Condition (20) states that the price of the permits should be equal to the social marginal damages caused by pollution. By (19), condition (21) may be rewritten as $z_2 = \bar{z}_2 + B^J$, i.e., the total amount of emissions realized in the second-period corresponds to the amount of permits defined at that period plus the permits banked from the first period. From the two equations, we observe that the quantity of permits distributed in period 2 is an increasing function of k (because $\eta' < 0$).

3.2. The First Period

In the first period, each agent has rational expectations on the behavior of all the other agents. Focusing on market microstructure rather than on intertemporal aspects, we assume that the discount rate is zero.

3.2.1. The Firm

In the first period, each firm knows k and solves

$$\max_{\{x_1^r\}} kmg(x_1) - a_1 \max\left\{\eta\left(\frac{a_1}{km}\right) - \bar{z}_1, 0\right\}$$
$$+ b_1 \max\left\{\bar{z}_1 - \eta\left(\frac{b_1}{km}\right), 0\right\} + kmg(x_2) - \pi_2[x_2 - \bar{z}_2] \tag{22}$$

subject to $x_2 = \eta(\frac{\pi_2}{km})$ and where

$$a_1 = \min\left\{a_1^1, a_1^2\right\} \quad \text{and} \quad b_1 = \max\left\{b_1^1, b_1^2\right\}. \tag{23}$$

Because of arbitrage (as discussed below), the only possible configuration of prices to be considered is $a_1 \geq b_1 \geq \pi_2$. This leads to emissions

$$x_1 = \left\{\begin{array}{lll} \eta\left(\frac{a_1}{km}\right) & \text{if} & \eta\left(\frac{a_1}{km}\right) - \bar{z}_1 > 0 \\ \bar{z}_1 & \text{if} & \eta\left(\frac{a_1}{km}\right) \leq \bar{z}_1 \leq \eta\left(\frac{b_1}{km}\right) \\ \eta\left(\frac{b_1}{km}\right) & \text{if} & \eta\left(\frac{b_1}{km}\right) - \bar{z}_1 < 0 \end{array}\right\}. \tag{24}$$

Up to now we have considered that firms do no bank permits. We now prove that this is indeed the case.

PROPOSITION 2: *Firms have no incentives to bank permits or are indifferent between banking and not banking.*

Proof: Banking of permits by firms depends on the level of π_2 with respect to $\{a_1, b_1\}$, knowing that $a_1 \geq b_1$. We cannot have $a_1 < \pi_2$ as this would lead to inter-temporal arbitrage: firms would buy and bank an infinite amount of permits in order to sell them in the second period.

Furthermore, we cannot have $b_1 < \pi_2$ because then firms would not sell any permits in the first period but would rather save and sell them at a higher price in the second period. There would then be no trade in the first period as there is no supply, and market makers would make no profits in the first period. But this cannot be an equilibrium for the market makers. Given π_2, there is a profitable deviation for market maker j consisting in setting (i) on the bid side: $b_1^j = \pi_2 + \varepsilon$ (where ε is a very small positive number) so that $S_1^j > 0$ and there is no banking by firms and (ii) on the ask side: a_1^j such that $D_1^j \leq S_1^j$. Then market maker j enjoys a profit $\Pi^j = [a_1^j - \pi_2]D_1^j - [\pi_2(+\varepsilon) - \pi_2]S_1^j \, \forall k$, which is positive as ε is very small.

Thus market makers will set prices such that firms either have no incentives to bank permits ($b_1 > \pi_2$) or are indifferent between banking and not banking ($b_1 = \pi_2$). ■

3.2.2. The Market

If the market makers know the value of k, then by a similar reasoning to the one presented for the last period, an equilibrium is reached when bid and ask prices equalize, i.e., when $a_1 = b_1 = \sigma_1$ such that the aggregate excess demand is zero, that is,

$$ED_1(\sigma_1, k) = \int_0^{\bar{m}} \left[\eta\left(\frac{\sigma_1}{km}\right) - \bar{z}_1\right] n(m)\, dm + B^J(k) = 0, \tag{25}$$

where B^J are the permits banked by the market makers. As in period 2, the market equilibrium resulting from the Bertrand competition between perfectly informed market makers leads to the walrasian market solution.

To characterize the market equilibrium, two cases must be distinguished:

Case 1: if $\exists \sigma_1 > \pi_2$ such that $ED_1(\sigma_1, k) = \int_0^{\bar{m}} [\eta(\frac{\sigma_1}{km}) - \bar{z}_1] n(m)\, dm = 0$ (i.e., the market clears), then

$$\int_0^{\bar{m}} \eta\left(\frac{\sigma_1}{km}\right) n(m)\, dm = \bar{z}_1 \quad \text{and} \quad B^J = 0. \tag{26}$$

Case 2: if $\nexists \sigma_1 > \pi_2$ such that $ED_1(\sigma_1, k) = \int_0^{\bar{m}} [\eta(\frac{\sigma_1}{km}) - \bar{z}_1] n(m)\, dm = 0$, then

$$\sigma_1 = \pi_2 \quad \text{and} \quad B^J = \bar{z}_1 - \int_0^{\bar{m}} \eta\left(\frac{\pi_2}{km}\right) n(m)\, dm. \tag{27}$$

Let $\tilde{k}(\bar{z}_1)$ be the value of k such that the market just clears at the price $\sigma_1 = \pi_2$. In other words, $\tilde{k}(\bar{z}_1)$ is such that $ED_1(\pi_2, \tilde{k}) = \int_0^{\bar{m}} [\eta(\frac{\pi_2}{\tilde{k}m}) - \bar{z}_1] n(m)\, dm = 0$. Given $\bar{z}_1$, if $k > \tilde{k}(\bar{z}_1)$, then $\sigma_1 > \pi_2$ (if k is high, production, pollution and demand of permits are high, driving the price of permits above π_2). On the contrary, if $k < \tilde{k}(\bar{z}_1)$, then $\sigma_1 = \pi_2$ (if k is low, production, pollution and demand of permits are low, driving the price of permits to its minimum level π_2, the permits in excess being banked).

$\tilde{k}$ is an increasing monotonous function of $\bar{z}_1$. Let $\check{z} = \tilde{k}^{-1}(\underline{k})$ and $\hat{z} = \tilde{k}^{-1}(\bar{k})$. Then three regimes may occur:

Regime A: if $0 < \bar{z}_1 < \check{z}$, then $\sigma_1 = \frac{k}{\tilde{k}(\bar{z}_1)}\pi_2 > \pi_2, \forall k \in [\underline{k}, \bar{k}]$ (never banking).

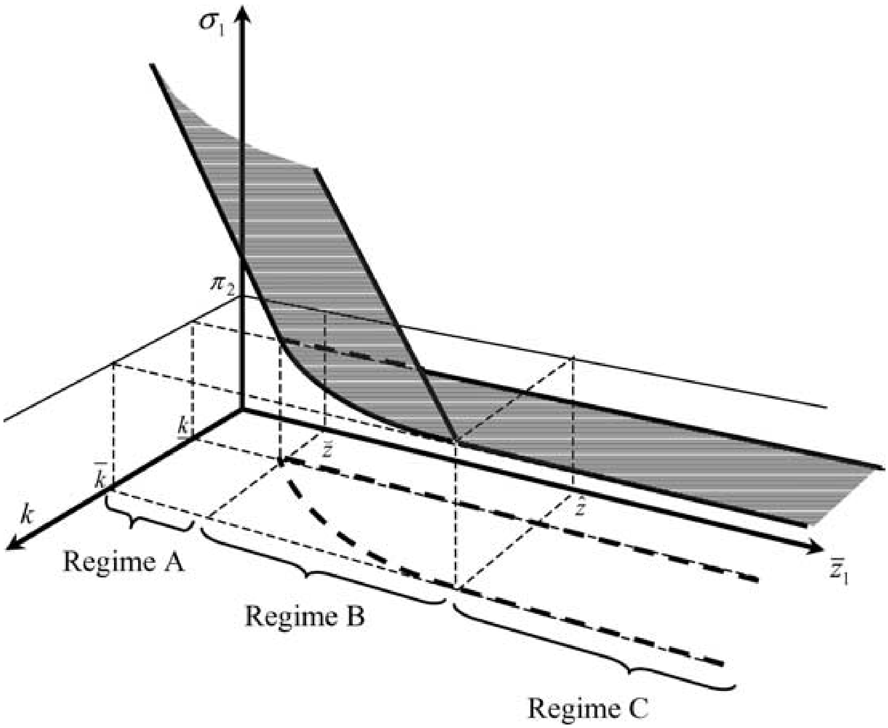

Figure 1: First-period permits price and the three regimes

Regime B: if $\check{z} \le \bar{z}_1 \le \hat{z}$, then $\sigma_1 = \frac{k}{\tilde{k}(\bar{z}_1)}\pi_2 > \pi_2$, if $k \in [\tilde{k}(\bar{z}_1), \bar{k}]$ (no banking) or $\sigma_1 = \pi_2$, if $k \in [\underline{k}, \tilde{k}(\bar{z}_1)]$ (banking).

Regime C: if $\hat{z} < \bar{z}_1$, then $\sigma_1 = \pi_2, \forall k \in [\underline{k}, \bar{k}]$ (always banking).

These regimes are illustrated in Figure 1, which shows σ_1 as a function of $\bar{z}_1$ and k.

3.2.3. The Agency

The environmental agency maximizes the expected social utility over the two periods. Because social utility in period 2 depends only on exogenous parameters, the problem reduces to

$$\max_{\{\bar{z}_1\}} E[U](\bar{z}_1) = \int_{\underline{k}}^{\bar{k}} f(k) \int_0^{\bar{m}} \left[kmg\left(\eta\left(\frac{\sigma_1}{km}\right)\right) - \pi_1 \eta\left(\frac{\sigma_1}{km}\right)\right] n(m)\, dm\, dk, \quad (28)$$

where σ_1 is determined as explained just above, depending on the value of $\bar{z}_1$ and k.

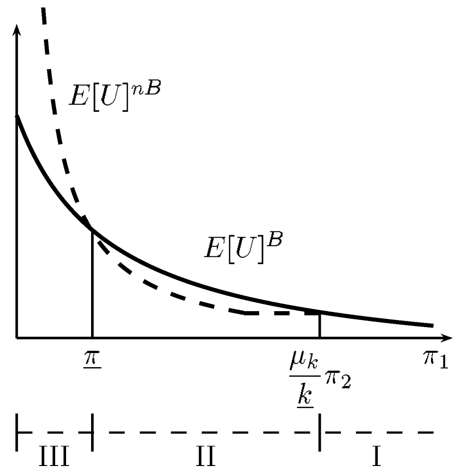

Figure 2: Optimal expected utility when banking is allowed (B) and when banking is not allowed (nB)

Since the optimal conditions are not easily tractable, we concentrate on a particular case where (i) the production functions are *isoelastic*, i.e., we suppose that $g(x) = x^{(1-\alpha)}/(1-\alpha)$ (with $\alpha \in]0, 1[$) and (ii) the density function $f(k)$ is *uniform*, i.e., $f(k) = 1/(\bar{k} - \underline{k})$ on $[\underline{k}, \bar{k}]$ with $\underline{k} > 0$.[9]

The results are summarized as follows:[10]

$$\bar{z}_1^B \left\{ \begin{array}{lll} = M\left[\dfrac{\mu_k}{\pi_1}\right]^{\frac{1}{\alpha}} & \text{if} \quad \pi_1 > \dfrac{\mu_k}{\underline{k}}\pi_2 & \text{Regime I} \\ = M\left[\dfrac{\bar{k}}{2\pi_1 - \pi_2}\right]^{\frac{1}{\alpha}} & \text{if} \quad \pi_2 < \pi_1 < \dfrac{\mu_k}{\underline{k}}\pi_2 & \text{Regime II} \\ \geq M\left[\dfrac{\bar{k}}{\pi_2}\right]^{\frac{1}{\alpha}} & \text{if} \quad \pi_1 < \pi_2 & \text{Regime III} \end{array} \right\},$$

where by definition: $\mu_k = (\bar{k} + \underline{k})/2$ is the mean of $f(k)$ and $M = \int_0^{\bar{m}} m^{\frac{1}{\alpha}} n(m)\, dm$. The optimal amount of permits $\bar{z}_1^B$ is decreasing with π_1 in both Regimes I and II because the higher the marginal willingness to pay for the environment (π_1), the lower the optimal level of pollution and, thus, of permits. It is constant under Regime III because it is not possible to increase the ambient pollution above a certain threshold, since the price of permits in the first period cannot fall below π_2 due to the possibility of banking.

[9]A uniform density function is usually assumed when one has no *a priori* knowledge of the distribution of the random event.

[10]Details of the computations are available from the authors upon request.

Figure 2 illustrates the optimal expected utility as a function of π_1. As suggested in this figure, the optimal expected utility $E[U]^B$ is decreasing under the three regimes. In Regime I and II, the expected utility does not decrease (with π_1) as quickly as in Regime III because the optimal level of pollution is not (Regime I) or not as much (Regime II) constrained by banking as in Regime III.

3.2.4. Complete Information

When all agents have perfect information about k, Regime II disappears. In this case, Figure 2 simplifies and banking takes place in Regime III, but not in Regime I.

3.3. The Role of Banking

What happens if banking is not allowed? In the second period, the analysis of Section 3.1 applies but without any permits being banked from the first period. The environmental agency then chooses $\bar{z}_2 = \int_0^{\bar{m}} \eta(\frac{\pi_2}{km})\, n(m)\, dm$, which leads the economy to exactly the same level of expected utility.

In the first period, the permit market price forms independently of the second period's permits price as banking is not allowed, in such a way that

$$\int_0^{\bar{m}} \eta\left(\frac{\sigma_1}{km}\right) n(m)\, dm = \bar{z}_1. \tag{29}$$

The problem of the environmental agency is thus to maximize (28) under the constraint (29). It can be shown that the solution, $\bar{z}_1^{nB}$, is the same solution as in Regime I when banking is allowed. Therefore, and as expected, allowing banking does not modify the expected utility in Regime I. It might, however, do so in Regimes II and III.

For the particular case (isoelastic production function, uniform density function), the comparison between the banking and the no banking cases is illustrated in Figure 2.[11]

We observe that the possibility of banking does not modify the expected utility when $\pi_1 > \frac{\mu_k}{\underline{k}}\pi_2$ (Regime I). Indeed, the amount of permits defined in the first period by the agency is so low that banking is never used.

However, when $\pi_1 < \frac{\mu_k}{\underline{k}}\pi_2$ (Regimes II and III), banking takes place and is responsible for two effects. The first one comes from the fact that banking

[11]The results follow from the shape of the expected utility with and without banking ($E[U]^B$ and $E[U]^{nB}$, respectively) as a function of π_1. First, and as shown above, $E[U]^{nB} = E[U]^B$ for $\pi_1 \geq \frac{\mu_k}{\underline{k}}\pi_2$. Second, it can be shown that $E[U]^B > E[U]^{nB}$ for $\pi_1 = \pi_2$ amounts to $\int_{\underline{k}}^{\bar{k}} k^{1/\alpha} f(k)\, dk > [\int_{\underline{k}}^{\bar{k}} kf(k)\, dk]^{\frac{1}{\alpha}}$ which is always true in accordance with the inequality of Hölder. Then, by convexity of $E[U]^B$ and $E[U]^{nB}$, we necessarily have that $E[U]^B > E[U]^{nB}$ on $[\pi_2; \frac{\mu_k}{\underline{k}}\pi_2[$ (i.e., in Regime II). Finally, the intersection at $\underline{\pi}$ necessarily exists because the two functions are continuous and because $E[U]^{nB} \to \infty$ as $\pi_1 \to 0$, whereas $E[U]^B$ is finite when $\pi_1 = 0$.

allows to modulate production and pollution in function of parameter k, particularly if k is high. Indeed if k is high, production will be high and its marginal utility low (other things being equal). With banking, the agents have the opportunity to sacrifice a fraction of this production for a better environment, keeping the extra permits for period 2. Without banking, this is not possible and pollution and production are determined by the quantity of permits which is fixed before the realization of k. Note that the flexibility allowed by banking does not work as well in the other way (i.e., when k is low) because borrowing is not allowed. Nevertheless, this first effect plays in favor of a bankable permit system.

The second effect concerns the comparison of the levels of pollution and production between periods. Banking forbids high levels of pollution and production to take place in the first period although this would increase welfare for relatively low values of the first period marginal willingness to pay for the environment, π_1. This second effect plays against allowing banking.

As illustrated in Figure 1, the result of these two effects depends of the value of π_1. Under Regime II and part of Regime III, banking is preferable. But for low values of π_1, the second effect prevails and the no banking situation is better.

3.4. Strategic Behavior and Asymmetry of Information

To conclude this section, we address a question raised by the informational structure of the model. The agency learns k through the observation of aggregate production or trades in permits and then determines the optimal quantity of permits for period 2 ($\bar{z}_2$). As a consequence one may wonder if there is an opportunity for the firms to manipulate, e.g., their level of production in order to increase the permits received in period 2.[12]

The answer is no because the firms are "informationaly small" (in the sense of Palfrey and Srivastava (1986)). Indeed, we assume that the agency learns k via the observation of aggregate quantities. Moreover, since there is a continuum of firms, the contribution of a certain firm to aggregate production or emissions is marginal. Therefore, a firm cannot manipulate the information.

4. Market Makers Imperfectly Informed

4.1. The Last Period

Since all agents know k in period 2, the solution for period 2 is exactly the same as in the Section 3.1.

[12]We are indebted to a referee of the journal to have drawn our attention to this question.

4.2. The First Period

4.2.1. The Firm

Since the firms know k, the solution for the firms in period 1 is exactly the same as in the Subsection 3.2.1.

4.2.2. The Market Makers

Aggregate demand and supply by firms are then

$$D_1(a_1, k) = \int_{\frac{a_1}{k\gamma(\bar{z}_1)}}^{\bar{m}} \left[\eta\left(\frac{a_1}{km}\right) - \bar{z}_1\right] n(m)\, dm \tag{30}$$

and

$$S_1(b_1, k) = \int_0^{\frac{b_1}{k\gamma(\bar{z}_1)}} \left[\bar{z}_1 - \eta\left(\frac{b_1}{km}\right)\right] n(m)\, dm. \tag{31}$$

Each market maker chooses $\{a_1^j, b_1^j\}$ so as to maximize its expected profit, i.e.,

$$\max_{\{a_1^j, b_1^j, B^j \geq 0\}} E[\Pi^j] = E\left[a_1^j D_1^j\left(a_1^j, a_1^{3-j}, k\right) - b_1^j S_1^j\left(b_1^j, b_1^{3-j}, k\right) + \pi_2 B^j(k)\right] \tag{32}$$

subject to $a_1^j \geq b_1^j \geq \pi_2$ and

$$D_1^j\left(a_1^j, a_1^{3-j}, k\right) + B^j(k) = S_1^j\left(b_1^j, b_1^{3-j}, k\right), \tag{33}$$

with

$$D_1^j\left(a_1^j, a_1^{3-j}, k\right) = D_1\left(a_1^j, k\right) 1_{\{a_1^j < a_1^{3-j}\}} \tag{34}$$

$$S_1^j\left(b_1^j, b_1^{3-j}\right) = S_1\left(b_1^j, k\right) 1_{\{b_1^j > b_1^{3-j}\}}. \tag{35}$$

Given the results for period 2, permits banked by market makers at $t = 1$ will be sold at price π_2 at $t = 2$, and $E[\pi_2 B^j(k)]$ are the expected profits for period 2.

PROPOSITION 3: *An equilibrium is reached when the market makers set their prices in such a way that*

$$a_1 = b_1 = \pi_2 \quad \text{if } \bar{z}_1 \geq \int_0^{\bar{m}} \eta\left(\frac{\pi_2}{\bar{k}m}\right) n(m)\, dm$$

$$a_1 > b_1 > \pi_2 \quad \text{otherwise.}$$

and such that, (i) their expected profits are null, i.e.,

$$E[\Pi] = E[a_1 D_1(a_1, k) - b_1 S_1(b_1, k) + \pi_2 B^J(k)] = 0, \tag{36}$$

(ii) there is no banking only when $k = \bar{k}$ *and* $\bar{z}_1 < \int_0^{\bar{m}} \eta(\frac{\pi_2}{km}) n(m)\, dm$*, otherwise*

$$B^J > 0, \tag{37}$$

and (iii) for $\bar{z}_1 < \int_0^{\bar{m}} \eta(\frac{\pi_2}{km}) n(m)\, dm$*, there is no profitable deviation, i.e.,*

$$\frac{\partial E[\Pi]}{\partial b_1} < 0 \text{ and } \frac{\partial E[\Pi]}{\partial a_1} + \frac{\partial E[\Pi]}{\partial b_1}\frac{db_1}{da_1} > 0 \tag{38}$$

where $\frac{db_1}{da_1} = \frac{\partial D_1/\partial a_1}{\partial S_1/\partial b_1}$.

Furthermore, if $[[a - \pi_2]D_1(a)]' > 0$*, then for* $\bar{z}_1 < \int_0^{\bar{m}} \eta(\frac{\pi_2}{km}) n(m)\, dm$*, such an equilibrium between market makers exists and is unique.*

Proof: The proof is available from the authors upon request.

When $b_1 > \pi_2$, we necessarily have a positive spread ($a_1 > b_1$) although market makers expected profits are null. Indeed, the permits that are banked (since ask and bid prices do not depend on the realization of k) are sold at the price π_2 although they have been bought at the price $b_1 > \pi_2$. Market makers would thus enjoy negative expected profits if they do not set $a_1 > b_1$.

It is an established result that the distribution of permits has no impact on the performance of the market when this market is walrasian. This is the case in Section 3. On the contrary, the results do depend on the allocation of the permits in Section 4. Indeed, the way the permits are allocated influences the volume of transactions and consequently, due to the spread between bid and ask prices, the total transaction costs.

4.2.3. The Agency

Aggregate production is

$$Y_2 = \int_0^{\bar{m}} kmg\left(\eta\left(\frac{\pi_2}{km}\right)\right) n(m)\; dm \tag{39}$$

in the second period and

$$Y_1 = \int_0^{\frac{b_1}{k\gamma(\bar{z}_1)}} kmg\left(\eta\left(\frac{b_1}{km}\right)\right) n(m)\, dm + \int_{\frac{b_1}{k\gamma(\bar{z}_1)}}^{\frac{a_1}{k\gamma(\bar{z}_1)}} kmg\,(\bar{z}_1)\, n(m)\, dm + \int_{\frac{a_1}{k\gamma(\bar{z}_1)}}^{\bar{m}} kmg\left(\eta\left(\frac{a_1}{km}\right)\right) n(m)\, dm \tag{40}$$

in the first period. The total amounts of emissions are, respectively,

$$z_2 = \int_0^{\bar{m}} \eta\left(\frac{\pi_2}{km}\right) n(m)\, dm \tag{41}$$

and

$$z_1 = \int_0^{\frac{b_1}{k\gamma(\bar{z}_1)}} \eta\left(\frac{b_1}{km}\right) n(m)\,dm + \int_{\frac{b_1}{k\gamma(\bar{z}_1)}}^{\frac{a_1}{k\gamma(\bar{z}_1)}} \bar{z}_1 n(m)\,dm + \int_{\frac{a_1}{k\gamma(\bar{z}_1)}}^{\bar{m}} \eta\left(\frac{a_1}{km}\right) n(m)\,dm. \tag{42}$$

The environmental agency's problem writes

$$\max_{\{\bar{z}_1, \bar{z}_2\}} E[Y_1 - \pi_1 z_1 + Y_2 - \pi_2 z_2] \tag{43}$$

subject to conditions (36) to (38), and where Y_1, Y_2, z_1, z_2 are defined by (39) to (42). Since the conditions associated with this problem are difficult to interpret, we solve it numerically for the particular case described in Subsection 3.2.3 ($g(x) = \frac{x^{1-\alpha}}{1-\alpha}$ with $0 < \alpha < 1$, $f(k) = 1/[\bar{k} - \underline{k}]$ on $[\underline{k}, \bar{k}]$ with $n(m) = \bar{m} = 1$).[13]

To summarize, we observe that:

Regime I: When $\pi_1 \leq \pi_2$, the solution is the same as when market makers are perfectly informed (first model):

- (i) there is no spread in the first period and $a_1 = b_1 = \pi_2$,
- (ii) the optimal amount of permits is constant w.r.t. π_1,
- (iii) the optimal expected social utility $E[U]^B$ is linearly decreasing with π_1.

Regime II: When $\pi_1 > \pi_2$,

- (i) there is a positive spread in the first period ($a_1 > b_1 > \pi_2$), and both prices and the spread are increasing with π_1,
- (ii and iii) the optimal amount of permits and expected utility are decreasing convex functions of π_1.

There is always banking except under Regime II when $k = \bar{k}$. On the contrary to what happens under Regime I, the solution differs when $\pi_1 > \pi_2$ whether the market makers are perfectly informed or not about the parameter k. When they are not perfectly informed, a positive spread occurs ($a_1 > b_1$) which is responsible for the non-equalization of the polluters' marginal abatement costs. This means that, for a given amount of emissions (pollution), the production is lower than when there is no spread.

[13]By use of the MATLAB 5.2 Optimization toolbox. Values of the parameters are $\alpha = .9$, $\bar{k} = 1.25$, $\underline{k} = .75$, $\pi_2 = 1$.

Table 1: Numerical results

	Banking				No Banking			
π_1	a_1	b_1	$\bar{z}_1^B$	$E[U]^B$	a_1	b_1	$\bar{z}_1^{nB}$	$E[U]^{nB}$
0.5	1	1	0.607	4.506	0.585	0.482	1.159	4.609
0.75	1	1	0.607	4.387	0.877	0.723	0.739	4.406
1	1	1	0.607	4.268	1.170	0.963	0.537	4.268
1.01	1.013	1.009	0.599	4.264	1.182	0.973	0.531	4.263
1.25	1.317	1.237	0.455	4.164	1.462	1.204	0.419	4.163
1.5	1.622	1.476	0.364	4.080	1.755	1.445	0.342	4.080
1.75	1.922	1.715	0.303	4.011	2.047	1.686	0.288	4.010
2	2.220	1.955	0.259	3.952	2.339	1.927	0.248	3.951
2.25	2.516	2.196	0.226	3.900	2.630	2.166	0.218	3.900
2.5	2.811	2.436	0.200	3.855	2.924	2.409	0.194	3.855

Finally, note that the spread is not symmetric w.r.t. π_1, the price of permits that would apply if there was no uncertainty (the difference $a_1 - \pi_1$ is higher than $\pi_1 - b_1$).[14]

It is now interesting to compare the situations prevailing with and without the possibility of banking. To illustrate the comparison with the situation with banking, we numerically solve the particular case of Subsection 4.2.3, this time without banking.[15] Results are summarized in Table 1.

Market makers are left with unsold permits in the first period when $k \neq \bar{k}$. These unsold permits are lost as banking is not permitted. In order to enjoy a non-negative expected profit, market makers must set a positive spread. The loss that they bear due to these unsold permits in the first period is necessarily lower when banking may take place, because market makers can sell them at the price π_2 in period 2. It is thus easier for them to satisfy both their budget and their non-negative expected profit constraints.[16]

[14]There is no reason for the market equilibrium (characterized by the equations $E[\Pi] = 0$ and $B^J = 0$ for $k = \bar{k}$) to lead to a symmetric spread w.r.t. π_1. Even in the particular case considered above (with uniform and thus symmetric density functions), the second equation leads to $\int_{\frac{a_1 \bar{z}_1^\alpha}{\bar{k}}}^{1} (\frac{m\bar{k}}{a_1})^{\frac{1}{\alpha}} - \bar{z}_1 \, dm = -\int_0^{\frac{b_1 \bar{z}_1^\alpha}{\bar{k}}} (\frac{m\bar{k}}{b_1})^{\frac{1}{\alpha}} - \bar{z}_1 \, dm$. One observes that asymmetry remains because of the convexity of the functions under the integrals w.r.t. m.

[15]When banking is not possible, the problem of the market makers is the same as the one described by (30) to (35) with $B^j = 0$ (see Germain et al. 2000).

[16]On the basis of numerical simulations, Germain et al. (2000) show that there exists no equilibrium with trades for relatively high uncertainty or for α relatively small. In some circumstances the uncertainty becomes so high that it is impossible for market makers to set prices such that their budget constraints are binding. The authors thus emphasize another role of banking in the presence of market makers: allowing for the existence of equilibria with trades which would not exist otherwise.

This explains the following observation. For $\pi_1 > \pi_2$ (Regime II), the expected utility is higher when banking is allowed. The lower loss under banking allows the market makers to set a lower spread, which leads to less inefficiency in production as the marginal abatement costs are closer to equalization across firms. In this regime, the agency defines in period 1 more permits than if banking is not allowed.

However, when $\pi_1 < \pi_2$ (Regime I), with banking the level of pollution is determined by the second period permits price π_2. Therefore, banking does not allow to increase the level of pollution (and of production) in the first period although this would increase expected utility. The lower π_1, the stronger this second effect.

As illustrated in Table 1 (where $E[U]^{nB}$ is the optimal expected utility without banking), this second effect might dominate the first one for some low values of π_1. On the contrary, for $\pi_1 > \pi_2$, the first effect dominates slightly.

Finally, note that as when banking is allowed, the spread is not symmetric w.r.t. π_1.

5. Conclusions

The purpose of this paper has been to analyze, in a two periods model, how the market structure of emission permits—their microstructure—influences the optimal policy to be adopted by the environmental agency. The microstructure used is one of a *quote driven market* type, which characterizes many financial markets. Market makers serve as intermediaries for trading permits by setting an ask price (i.e., a price at which they are ready to sell permits) and a bid price (i.e., a price at which they are ready to buy permits). The possibility of banking permits from one period to the other has also been introduced.

Two situations are considered. In the first model, market makers are perfectly informed about the firms' technology. It is shown that the Bertrand competition between the market makers leads to the walrasian equilibrium. When one compares banking with no banking, two opposite effects occur. On the one hand, banking may offer more flexibility in the use of the permits. On the other hand, because of intertemporal arbitrage, it may prevent desired low permit price levels in the first period. The result of these two effects on the interest to allow banking or not depends crucially on the marginal willingness to pay for the environment in period 1 (π_1) given its level in period 2 (π_2).

In the second model, the market makers are imperfectly informed about the polluters' technology in period 1. We show that market makers may set a positive spread between bid and ask prices in period 1. This spread forbids the marginal abatement costs to equalize, which creates some inefficiency. The bid and ask prices surround π_1, but not symmetrically. When banking is not allowed, the spread is larger because when they are left with unsold permits in period 1, the market makers cannot sell them in period 2. This plays in favor of banking. However, the opposite effect due to intertemporal arbitrage present in the first model is also present here. Once again the result of these two effects on the interest to allow banking or not depends crucially on π_1. Even if this dependence varies between the two models, our simulations show for both models that banking leads to a lower expected social utility for low values of π_1, and to a higher (or at least as high) level for high values of π_1.

However, since these results concern a particular case, the analysis should be extended to other contexts before drawing general conclusions on the interest of allowing banking or not.[17] For example one could consider a stock pollutant in the context of non-linear damages to the environment.

Another interesting extension would be to consider a framework where a finite number of firms could strategically manipulate the information (i.e., their production and pollution levels) in period 1 in order to receive more permits in period 2.

References

BIAIS, B. (1990) Formation des prix sur les marchés de contrepartie: une synthèse de la littérature récente, *Revue Economique* **5**, 775–788.

BIAIS, B., T. FOUCAULT, and P. HILLION (1997) *Microstructure des marchés financiers: institutions, modèles et tests empiriques*, Presses Universitaires de France: Paris.

CRONSHAW, M. B., and J. B. KRUSE (1996) Regulated firms in pollution permit markets with banking, *Journal of Regulatory Economics* **9**, 179–189.

DALES, J. H. (1968) *Pollution, Property and Prices*. University of Toronto Press: Toronto.

GERMAIN, M., S. LOVO, and V. VAN STEENBERGHE (2000) De l'impact de la microstructure d'un marché de permis de polluer: IRES Discussion Paper 2000/10, Université Catholique de Louvain, Forthcoming in *Annales d'Economie et de Statistique*.

HAGEM, C., and H. WESTSKOG (1998) The design of a dynamic tradeable quota system under market imperfections, *Journal of Environmental Economics and Management* **36**, 89–107.

HAHN, R. W. (1984) Market power and transferable property rights, *Quarterly Journal of Economics* **99**, 753–765.

KLING, C., and J. RUBIN (1997) Bankable permits for the control of environmental pollution, *Journal of Public Economics* **64**, 101–115.

MONTERO, J.-P. (1998) Marketable pollution permits with uncertainty and transaction costs, *Resource and Energy Economics* **20**, 27–50.

MONTGOMERY, W. D. (1972) Markets in licences and efficient pollution control programs, *Journal of Economic Theory* **5**, 395–418.

O'HARA, M. (1995) *Market Microstructure Theory*. Blackwell: Cambridge, MA.

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[17] In this sense, we agree with Yates and Cronshaw's conclusion: "it is difficult to make general statements about the relative merits of increased decentralization [i.e., allowing banking] when there is asymmetric information" (Yates and Cronshaw 2001, p. 116).

PALFREY, T., and S. SRIVASTAVA (1986) Private information in large economies, *Journal of Economic Theory* **39**, 34–58.

PHANEUF, D., and T. REQUATE (2002) Incentives for investment in advanced pollution abatement techonogy in emission permit markets with banking: *Environmetal and Resource Economics* **22**, 369–390.

REQUATE, T. (1998) Does banking of permits improve welfare? Draft manuscript, Departement of Economics, University of Heidelberg.

RUBIN, J. (1996) A model of intertemporal emission trading, banking and borrowing, *Journal of Environmental Economics and Management* **31**, 269–286.

SCHENNACH, S. M. (2000) The economics of pollution permit banking in the context of Title IV of the 1990 Clean Air Act Amentdments, *Journal of Environmental Economics and Management* **40**, 189–210.

STAVINS, R. N. (1995) Transaction costs and tradable permits, *Journal of Environmental Economics and Management* **29**, 133–148.

YATES, A. J., and M. B. CRONSHAW (2001) Pollution permit markets with intertemporal trading and asymetric information, *Journal of Environmental Economics and Management* **42**, 104–118.