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Deterring Non-compliance in Dynamic Emissions Trading Programs: Does Allowing Permit Banking Call for a Different Enforcement Strategy?

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Abstract: We construct a dynamic model of compliance and enforcement in an emissions trading program to determine whether enforcing an emissions trading program that allows permit banking is different from enforcing a trading program that does not. A key component of the model is that firms are required to submit a report of their emissions in every time period. We find that when banking is allowed, firms have an incentive to under-report their emissions in order to save additional permits for the future; no such incentive exists when banking is prohibited. Deterring this incentive to under-report emissions by firms that can bank permits requires a more stringent enforcement strategy than when banking is prohibited.

JEL Codes: *L51, Q28.*

1. Introduction

Whether facilities should be allowed to bank transferable emissions permits for future use or sale is one of the fundamental issues that policymakers must resolve when designing an emissions trading program. The ability to bank transferable permits allows facilities the freedom to move emissions and abatement costs through time, presumably in a cost-effective manner, while prohibiting permit banking allows regulators to meet annual aggregate emissions targets consistently. The two most prominent emissions trading programs in the United States take different approaches to this issue. The Regional Clean Air Incentives Market (RECLAIM) of Southern California prohibits banking of emissions permits, while the Sulfur Dioxide (SO_2) Allowance Trading program allows banking without restriction.[1] During Phase I of the SO_2 program (1995-1999), facilities banked just over 30% of the total allocation of SO_2 allowances.[2]

In this paper we answer a fundamental design question concerning bankable emissions permits: Does enforcing an emissions trading program that allows permit banking differ from

[1] Neither program, nor any other to our knowledge, allows facilities to borrow permits from future allocations. In this paper we do not address compliance and enforcement issues when permits can be borrowed from future allocations.

[2] Calculation by authors based on data from *Acid Rain Program: Annual Progress Report, 2000* (http://www.epa.gov/airmarkets/cmprpt/arp00/index.html).

enforcing a trading program that does not? There are now a fair number of papers that have addressed theoretical issues concerning permit banking [Cronshaw and Kruse (1996), Rubin (1996), Kling and Rubin (1997), and Schennach (2000)], and a somewhat larger literature that examines compliance behavior and enforcement of emissions trading programs [Malik (1990, 1992), Keeler (1991), van Egteren and Weber (1996), Stranlund and Dhanda (1999), Stranlund and Chavez (2000), and a few others]. However, the models of permit banking assume away the issue of non-compliance, and the models of compliance and enforcement are static models that do not allow permit banking. Thus, this paper can be viewed as a bridge across the two lines of research that addresses a timely and practical policy problem.

Our approach is to extend the static model of enforcing an emissions trading program presented by Stranlund and Chavez (2000) to a dynamic environment in which firms may or may not save emissions permits for the future. A key component of the model is the requirement that firms submit an emissions report in every time period.[3] The enforcement objective is to deter all violations—under-reporting of emissions and failing to hold enough permits to cover emissions—in the cheapest manner possible. This objective is motivated by the very high compliance rates achieved in the SO_2 and RECLAIM programs. In Phase I of the SO_2 program all firms were perfectly compliant [U.S. EPA (1999, 2000)]. Compliance rates in the RECLAIM program ranged between 85% and 95% between 1994 and 1999 [South Coast Air Quality Management District (1998, 2000)]. It is clear that the enforcement strategies for these programs

[3] Self-reporting is an important element of both the RECLAIM and SO_2 programs. Detailed descriptions of the enforcement strategies used in these programs, including provisions for self-reporting, can be found in Stranlund, Chavez, and Field (2002). Except for Stranlund and Chavez (2000), others who have considered the role of self-reporting have focused exclusively on enforcing standards [e.g., Malik (1993), Kaplow and Shavell (1994), and Livernois and McKenna (1999)].

were designed to achieve high rates of compliance; hence, this appears to be an important policy objective that deserves our attention.

The primary contribution of this paper is our finding that compliance incentives and the enforcement strategies necessary to deter non-compliance are different in systems with and without permit banking. The fundamental difference lies in deterring incentives to submit false emissions reports. In the absence of the ability to bank permits, the only reason a firm would under-report its emissions (firms will never have an incentive to over-report their emissions) is to cover up the fact that it doesn't hold enough permits to cover its emissions for the period. With bankable permits, a firm has an additional motivation to under-report its emissions: under-reporting, if undiscovered by authorities, generates additional permits for future use or sale.

Deterring this incentive to under-report emissions implies that penalties for reporting violations play a critical role when permits can be banked—compliance cannot be achieved without these penalties. In contrast, penalties for reporting violations are not necessary when permit banking is prohibited. These results have clear policy implications that run contrary to actual practice. Despite the importance of permit banking in the SO_2 program there are no explicit provisions for penalizing reporting violations. Instead facilities face very demanding technological and process requirements for monitoring emissions and submitting emissions reports to the EPA. In the RECLAIM program, which prohibits banking, facilities also must meet rigorous technological requirements for generating and reporting emissions. In contrast to the SO_2 program, they also face explicit penalties for submitting false emissions reports.

We also find that the enforcement strategy necessary to deter non-compliance in an emissions trading program with banking is more stringent that what is required when banking is prohibited. More specifically, the cost-effective enforcement strategy that deters noncompliance in the absence of banking opportunities would not be completely effective in deterring non-compliance if it were applied to a program with bankable permits. From a different perspective, given identical prices in trading programs with and without permit banking, more enforcement effort must be expended when permits can be banked.

However, this conclusion does not imply straightaway that more enforcement effort must be applied when banking is allowed, because deterrence in emissions trading programs calls for tying the enforcement instruments (monitoring and penalties) to equilibrium permit prices, and these prices will evolve differently in banking and non-banking trading programs. Analyzing the relative enforcement requirements of banking and non-banking programs requires that we combine our findings about effective enforcement strategies with a model of how permit prices evolve under the two regimes. To date, Schennach (2000) has provided the most complete characterization of the evolution of permit prices for bankable permits. Enforcement strategies that induce full compliance allow us to combine our results with her characterization of permit price paths to show that emissions trading with banking does indeed require more enforcement effort, except if the equilibrium price of bankable permits falls significantly below the price that would prevail if banking was prohibited.

2. A model of compliance in a dynamic emissions trading program

The analysis of this paper is based on a model of a risk-neutral firm in a dynamic emissions trading program that lasts T periods. Let x_t be the number of permits the firm holds at the beginning of period t. Each permit confers the legal right to release one unit of emissions. A common element of the SO_2 Allowance Trading and RECLAIM programs is that a permit shortfall in a period—the firm does not hold enough permits to cover its emissions for the period— is deducted from the firm's endowment of permits in the next period on a one to one basis. This is true in our model as well. Therefore, x_t includes the firm's predetermined endowment of permits, $\bar{l}_t$, plus permits saved from previous periods if this is allowed, or less permits deducted because of a violation discovered in the previous period. The firm is not allowed to borrow permits from the future for current compliance purposes.

During period t the firm chooses its emissions e_t. The firm has an abatement cost function, $c(e_t)$, which is strictly decreasing and convex, and does not vary over the life of the program. During period t the firm also chooses how many permits l_t to purchase ($l_t > 0$) or sell ($l_t < 0$). As in the RECLAIM and SO_2 programs, a system is in place to track emissions permits so that at any point in time the regulator has perfect information about the number of permits each firm holds. Furthermore, permits trade in period t at a competitive price p_t.

At the end of period t the firm submits a report of its emissions r_t. With self-reporting of emissions two types of violations are possible: a *permit violation* occurs when the firm holds insufficient permits to cover its emissions, and a *reporting violation* occurs when the firm under-reports its emissions. Implicit in the emissions report is a report of the firm's compliance status and whether it is banking permits for the future, if allowed. If at the end of t, reported emissions exceed the firm's permit holdings, $r_t > (x_t + l_t)$, then the firm is reporting a permit violation. If $r_t \leq (x_t + l_t)$, then the firm is reporting that it is permit compliant, and if $r_t < (x_t + l_t)$, then it is reporting that it is banking permits. Of course, a firm's emissions report may differ from its actual emissions. If $e_t > (x_t + l_t)$, there is an actual permit violation; if $e_t \leq (x_t + l_t)$, then the firm is permit compliant, and if $e_t < (x_t + l_t)$, it has excess permits to save for the future. If the firm misrepresents its emissions in period t, then $e_t - r_t > 0$. A firm is never motivated to over-report its emissions; hence $e_t - r_t \geq 0$ for all t.

After the firm submits its emissions report, an audit is conducted with a known probability π_t. The audit uncovers the firm's true emissions for the period, which are compared to the firm's permit holdings and emissions report to determine its compliance status.[4] We follow Harford's (1987) approach to modeling penalties. If a firm reports a permit violation, a penalty of $f(r_t - (x_t + l_t))$ is imposed automatically. If a firm is audited and found to have under-reported its emissions so that $e_t - r_t > 0$, a penalty for the reporting violation, $g(e_t - r_t)$, is imposed. Of course, if a firm does not hold enough permits to cover its emissions and under-reports its emissions, it hasn't reported the full extent of its permit violation. If this is discovered by an audit the firm faces an incremental penalty for its unreported permit violation, $f(e_t - (x_t + l_t)) - f(r_t - (x_t + l_t))$. The penalty functions are strictly increasing and convex for positive reporting and emissions violations, and do not vary over the life of the program.[5]

Since the firm is not penalized when it is compliant, marginal penalties are discontinuous at points of compliance. The right hand derivatives of f and g at zero permit and reporting violations are $f'_+(0) = f'(0) > 0$ and $g'_+(0) = g'(0) > 0$. These are interpreted as the penalties for arbitrarily small permit and reporting violations, respectively. The left hand derivatives of f and g at zero permit and reporting violations are $f'_-(0) = g'_-(0) = 0$. For actual and reported permit banks; that is, $e_t - (x_t + l_t) < 0$ and $r_t - (x_t + l_t) < 0$, $f'(e_t - (x_t + l_t)) = f'(r_t - (x_t + l_t)) = f'_-(0) = 0$.

Combining the elements defined thus far yields the firm's single period expected costs,

$$\begin{aligned} v(e_t, l_t, r_t, x_t) = {} & c(e_t) + p_t l_t + f(r_t - (x_t + l_t)) \\ & + \pi_t [g(e_t - r_t) + f(e_t - (x_t + l_t)) - f(r_t - (x_t + l_t))]. \qquad [1] \end{aligned}$$

[4] We do not allow the enforcement authority to audit past behavior. Audits are assumed to check for current compliance only.

[5] Strict convexity of the penalty functions is not necessary for our analysis—all of our results hold as well under constant marginal penalties.

The firm's permit holdings at the beginning of a period depend on its choices in the previous period. Although we assume that all uncertainty about x_{t+1} is resolved by the start of t + 1, from the perspective of period t choices, x_{t+1} is a random variable because of incomplete monitoring at the end of t. If an audit is conducted in t and the firm did not hold enough permits to cover its emissions in that period, its actual permit shortfall, $e_t - (x_t + l_t) > 0$, is deducted from its t + 1 endowment of permits, $\bar{l}_{t+1}$. If an audit is conducted in t and the firm holds excess permits, $e_t - (x_t + l_t) < 0$, and if banking is allowed, this permit bank is added to $\bar{l}_{t+1}$. If an audit is not conducted the firm's reported permit shortfall, $r_t - (x_t + l_t) > 0$, or bank, $r_t - (x_t + l_t) < 0$, is carried forward. Thus, from the perspective of period t choices, the expected number of permits the firm will begin period t + 1 with is

$$\begin{aligned} E_t(x_{t+1}) &= \bar{l}_{t+1} + \pi_t (x_t + l_t - e_t) + (1 - \pi_t)(x_t + l_t - r_t) \\ &= \bar{l}_{t+1} + x_t + l_t - \pi_t e_t - (1 - \pi_t) r_t, \qquad [2] \end{aligned}$$

where the subscript on the expectation operator indicates that the expectation is from the perspective of period t.

Whether or not the firm is allowed to bank permits is modeled as an upper-bound constraint on its report of excess permits, $x_t + l_t - r_t \leq b$, where b is a non-negative constant.[6] In the absence of a banking opportunity, $b = 0$. In a banking program b is strictly positive. Constraining the size of the bank when permit banking is allowed is a necessary technical requirement that arises because when the firm holds enough permits to cover its emissions, its objective function becomes linear in its permit market transactions l_t.[7]

[6] This constraint and $e_t - r_t \geq 0$ imply that the firm's actual number of excess permits, $x_t + l_t - e_t$, does not exceed b.

[7] Rubin (1996) and Kling and Rubin (1997) impose a similar constraint.

The firm's objective is to choose a time path of emissions, permit transactions, and emissions reports to minimize its discounted sum of expected costs, subject to [2], the banking constraint $x_t + l_t - r_t \leq b$, and the constraint that the firm will never report that its emissions exceed its actual emissions, $e_t - r_t \geq 0$. That is, the firm chooses $\{e_t, l_t, r_t\}$, $(t = 0,\ldots, T)$, to solve

$$\begin{aligned}
&\min E\left[\sum_{t=0}^{T} \beta^t v(e_t, l_t, r_t, x_t)\right] \\
&s.t. \;\; E_t(x_{t+1}) = \bar{l}_{t+1} + x_t + l_t - \pi_t e_t - (1 - \pi_t) r_t, \qquad t = 0, 1, \ldots, T \\
&\qquad x_t + l_t - r_t \leq b, \qquad t = 0, 1, \ldots, T \\
&\qquad e_t - r_t \geq 0, \qquad t = 0, 1, \ldots, T \\
&\qquad x_0 = \bar{l}_0,
\end{aligned} \qquad [3]$$

where β is the discount factor, which is assumed to be constant over the life of the program.

Define $J_t(x_t)$ as minimum expected discounted costs from period t on through the last period, given the firm has x_t permits at the beginning of t. The stochastic dynamic programming equation is

$$J_t(x_t) = \min_{e_t, l_t, r_t} v(e_t, l_t, r_t, x_t) + \beta E_t[J_{t+1}(x_{t+1})], \qquad [4]$$

subject to the constraints specified in [3].

We assume that the enforcement authority's objective is to induce full compliance at least cost. Given full compliance in periods $t + 1$, $t + 2$, …, T, we derive the compliance incentives for the firm in period t. That is, we derive the firm's optimal choices of e_t, l_t, and r_t given full compliance in all future periods. By induction, from the period t choice strategies of the firm, we will derive enforcement strategies that will induce perfect compliance in every period t except the last. For the appropriate enforcement strategy for the last period, we will apply the results of Stranlund and Chavez (2000).[8]

If enforcement induces perfect compliance in each period $j = t + 1,\dots,T$, then for each j the firm submits a truthful emissions report so that $e_j = r_j$, and is permit compliant so that $l_j + x_j \geq e_j$. Note that if permit banking is prohibited, $l_j + x_j = e_j$. If permits can be saved for the future, $l_j \in [e_j - x_j, e_j - x_j + b]$. The upper bound indicates that the firm cannot bank more than b permits, while the lower bound indicates that the firm holds enough permits to cover its emissions.

Full compliance in every $j = t + 1,\dots,T$, will leave the firm's objective linear in l_j (this will be verified later). Therefore, l_j will often be indeterminate. Let us suppose that the number of permits the firms chooses to bank in j is a_j. Then, permit compliance in period j implies

$$l_j = e_j - x_j + a_j. \qquad [5]$$

In the final period, $a_T = 0$ whether permits are bankable or not. For all previous periods, $a_j = 0$ when banking is prohibited, and $a_j \in [0, b]$ when permits can be banked.

The following lemma specifies $E_t[J_{t+1}(x_{t+1})]$ up to a constant. It is proved in the appendix.

Lemma 1: *Given full compliance in periods* $j = t + 1,\dots,T$, $E_t[J_{t+1}(x_{t+1})] = -p_{t+1}E_t(x_{t+1}) + C$, *for some constant C.*

Incorporating the state equation [2], we have

$$E_t[J_{t+1}(x_{t+1})] = -p_{t+1}(\bar{l}_{t+1} + x_t + l_t - \pi_t e_t - (1 - \pi_t)r_t) + C. \qquad [6]$$

We are now ready to specify the dynamic programming equation in complete detail. Combining [1] and [4], the value function in any period $t = 0,\dots,T-1$ is

[8] This approach is equivalent to deriving the appropriate enforcement strategies by backward induction.

$$J_t(x_t) = \min_{e_t, l_t, r_t} \quad c(e_t) + p_t l_t + f(r_t - (x_t + l_t))$$

$$+ \pi_t [g(e_t - r_t) + f(e_t - (x_t + l_t)) - f(r_t - (x_t + l_t))] + \beta E_t[J_{t+1}(x_{t+1})]$$

$$s.t. \quad e_t - r_t \geq 0$$

$$r_t - (x_t + l_t) + b \geq 0. \qquad [7]$$

$E_t[J_{t+1}(x_{t+1})]$ is specified in equation [6], which incorporates the state equation [2]. The Lagrange equation for [7] is

$$\theta_t = c(e_t) + p_t l_t + f(r_t - (x_t + l_t)) + \pi_t [g(e_t - r_t) + f(e_t - (x_t + l_t)) - f(r_t - (x_t + l_t))]$$

$$+ \beta E_t[J_{t+1}(x_{t+1})] - \mu_t(e_t - r_t) - \gamma_t(r_t - (x_t + l_t) + b).$$

Using [6], the Kuhn-Tucker conditions are:

$$\partial\theta_t/\partial e_t = c'(e_t) + \pi_t [g'(e_t - r_t) + f'(e_t - (x_t + l_t))] + \beta p_{t+1}\pi_t - \mu_t = 0\ ; \qquad [8\text{-a}]$$

$$\partial\theta_t/\partial l_t = p_t - f'(r_t - (x_t + l_t)) - \pi_t [f'(e_t - (x_t + l_t)) - f'(r_t - (x_t + l_t))] - \beta p_{t+1} + \gamma_t = 0; \qquad [8\text{-b}]$$

$$\partial\theta_t/\partial r_t = f'(r_t - (x_t + l_t)) - \pi_t [g'(e_t - r_t) + f'(r_t - (x_t + l_t))] + \beta p_{t+1}(1 - \pi_t) + \mu_t - \gamma_t = 0; \qquad [8\text{-c}]$$

$$\partial\theta_t/\partial\mu_t = r_t - e_t \leq 0,\ \mu_t \geq 0,\ \mu_t \times (r_t - e_t) = 0; \qquad [8\text{-d}]$$

$$\partial\theta_t/\partial\gamma_t = -(r_t - (x_t + l_t) + b) \leq 0,\ \gamma_t \geq 0,\ \gamma_t \times (r_t - (x_t + l_t) + b) = 0. \qquad [8\text{-e}]$$

We assume that (8a-e) are necessary and sufficient to determine the firm's optimal choices of emissions, permit transactions, and emissions reports.[9]

[9] As noted previously, when banking is allowed the firm's choice of permit transactions will often be indeterminate when faced with an enforcement strategy that induces its full compliance.

3. Deterrence with and without banking

In this section we derive the period-*t* enforcement strategies to achieve full compliance in order to determine the extent to which enforcing an emissions trading program with banking is different from enforcing one without. It is important to recall that all period-*t* results are derived under the assumption of full compliance in all future periods. All of the results of this section are proved in the appendix, except those involving the last period of the program. The analysis of compliance in the last period is static, the results of which are presented in Stranlund and Chavez (2000). We will only state their results and refer the reader to their paper for proofs.[10]

3.1 Enforcing dynamic emissions trading programs

We begin with the firm's choice of emissions in period t, provided enforcement induces perfect compliance in all future periods. In every period the firm chooses its emissions to equate its marginal abatement costs with the prevailing permit price in that period. A number of authors have noted that this choice is independent of the enforcement strategy the firm faces, and whether it is compliant or not [the first appears to be Malik (1990)].

Proposition 1: *Emissions are chosen so that* $c'(e_t) + p_t = 0$.

In the last period, e_T is chosen so that $c'(e_T) + p_T = 0$.

To see this rewrite the Kuhn-Tucker condition [8-b] assuming that enforcement in t will induce perfect compliance. Since the firm faces no penalties, $\partial\theta_t/\partial l_t = p_t - \beta p_{t+1} + \gamma_t = 0$. Clearly l_t cannot be determined uniquely except when $p_t \neq \beta p_{t-1}$. If $p_t > \beta p_{t+1}$ so that real permit prices are declining, the firm will purchase as few permits as possible, or sell as many as possible, to maintain permit compliance $(l_t + x_t = e_t)$. If $p_t < \beta p_{t+1}$ so that real permit prices are increasing, the firm will bank as many permits as possible. Its choice of l_t is indeterminate when $p_t = \beta p_{t+1}$. Cronshaw and Kruse (1996), Rubin (1996), Kling and Rubin (1997), and Schennach (2000) all note that if firms are banking permits, $p_t = \beta p_{t+1}$ must hold as an equilibrium condition.

[10] Alternatively, we will provide the proofs upon request.

An effective enforcement strategy will have two parts, one that guarantees truthful emissions reporting and another that guarantees that the firm holds enough permits to cover its emissions in every time period. The fundamental difference between enforcing an emissions trading program with permit banking and enforcing one without lies in deterring different motivations for submitting false emissions reports. When banking is prohibited, a firm that holds enough permits to cover its emissions will never under-report its emissions, because doing so would imply that it is reporting that it has excess permits, which have no value. Therefore, the only time a firm may be motivated to submit a false emissions report when it cannot bank permits is when it holds insufficient permits to cover its emissions for the period. The following proposition reveals how this can be deterred.

Proposition 2: *If permit banking is prohibited, the firm provides a truthful emissions report in period t if* $p_t \leq \pi_t [g'(0) + f'(0) + \beta p_{t+1}]$.[11]

The strategy for eliciting truthful emissions reports is a simple comparison between the prevailing permit price in a period, p_t, which captures the marginal benefit of *not* purchasing permits to cover un-reported emissions, and the expected marginal costs of under-reporting. The cost of a slight reporting violation consists of the penalty for this violation, $g'(0)$, plus the penalty for the permit violation the firm has attempted to cover up, $f'(0)$, as well as the discounted value of permits deducted from the firm's allocation in the next period, βp_{t+1}.

[11] In fact, the necessary and sufficient condition for eliciting truthful reporting is $p_t \leq \pi_t [g'(0) + f'(e_t - (x_t + l_t)) + \beta p_{t+1}]$. As a rule for enforcement, this condition is problematic because it requires knowledge of emissions, which can only be determined by an audit. Replacing $f'(e_t - (x_t + l_t))$ with $f'(0)$ preserves the incentive for truthful reporting, because the strict convexity of f implies $f'(e_t - (x_t + l_t)) \geq f'(0)$.

Although the only motivation that a firm in a system without banking has to submit a false emissions report is to cover up a permit violation, a firm in a system with bankable permits has another motivation. When permit banking is allowed, a firm that holds enough permits to cover its emissions for a period may wish to under-report its emissions in order to save additional permits for the future. Deterring this sort of under-reporting is addressed by our next proposition.

Proposition 3: *Suppose that permit banking is allowed. A firm that holds enough permits to cover its emissions in period t will provide a truthful report of its emissions for this period if and only if* $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$.

Notice that the marginal penalty for a permit violation f' does not come into play in Proposition 3, because the firm is assumed to be permit compliant. For a firm that is not permit compliant, however, this penalty again serves as a deterrent to under-reporting of emissions.

Proposition 4: *Continue to assume that banking is allowed. A firm that is not permit compliant in period t will provide a truthful report of its emissions if* $p_t \leq \pi_t [g'(0) + f'(0) + \beta p_{t+1}]$.[12]

Because of the inclusion of $f'(0)$ in the strategy of Proposition 4 and its exclusion in Proposition 3, it is clear that the amount of monitoring necessary to deter under-reporting when banking is allowed is less when the firm does not hold enough permits to cover its emissions than when it does hold enough permits. However, permit compliance cannot be determined without an audit so an enforcer cannot distinguish a priori between compliant and non-compliant firms. Therefore, to deter all reporting violations the enforcer must chose the more demanding strategy. We conclude that in any period $t = 0,\ldots,T - 1$ of an emissions trading

[12] As when banking is not allowed, the necessary and sufficient condition for eliciting truthful reporting in this case is $p_t \leq \pi_t [g'(0) + f'(e_t - (x_t + l_t)) + \beta p_{t+1}]$.

program with permit banking, deterring all reporting violations requires that the enforcement strategy satisfy $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$.

A sufficient strategy for deterring under-reporting of emissions in the last period is the same whether banking is allowed or not. The strategy is $p_T \leq \pi_T [g'(0) + f'(0)]$. In the last period of a program with banking, a permit compliant firm will not under-report its emissions, because there is no motivation to save permits for the future. Therefore, the strategy in the last period must only confront a firm's motivation to under-report its emissions because it is trying to cover up a permit violation.

Now that we have specified what is necessary to elicit truthful emissions reports with and without banking, we need to make sure that a firm chooses to be permit compliant in period *t*.

Proposition 5: *Whether banking is allowed or not, given an appropriate strategy to elicit truthful emissions reports, the firm is permit compliant in t if and only if* $p_t \leq f'(0) + \beta p_{t+1}$. *In the last period the firm is permit compliant if and only if* $p_T \leq f'(0)$.

Given a strategy to elicit truthful emissions reports, a firm that is not permit compliant will report this violation and incur the certain penalty for the violation. In all but the last period, this consists of the penalty for the permit violation plus the discounted value of permits deducted from the next period's allocation. In the last period, only the penalty for the permit violation is assessed. If the price of purchasing enough permits to cover emissions in any period is less than the marginal cost of being non-compliant, the firm will choose to be permit compliant.

Combining our results about deterring reporting and permit violations yields the following: Guaranteeing that firms submit truthful emissions reports and hold enough permits to cover their emissions in every period of a trading program without banking requires

$$p_t \leq \pi_t\,[g'(0) + f'(0) + \beta p_{t+1}] \text{ and } p_t \leq f'(0) + \beta p_{t+1}, \text{ for all } t = 0,\ldots,T - 1;$$
$$p_T \leq \pi_T\,[g'(0) + f'(0)] \text{ and } p_T \leq f'(0). \qquad [9]$$

Guaranteeing complete compliance in every period when banking is permitted requires

$$p_t \leq \pi_t\,[g'(0) + \beta p_{t+1}] \text{ and } p_t \leq f'(0) + \beta p_{t+1}, \text{ for all } t = 0,\ldots,T - 1;$$
$$p_T \leq \pi_T\,[g'(0) + f'(0)] \text{ and } p_T \leq f'(0). \qquad [10]$$

Suppose that the penalty functions are fixed and $g'(0)$ and $f'(0)$ are high enough so that [9] and [10] can be satisfied. Enforcement that satisfies these conditions will induce full compliance, implying that no resources need to be expended to assess and collect fines. Therefore, enforcement costs are minimized by choosing audit probabilities so that the weak inequalities in [9] and [10] that involve these probabilities hold with strict equality.

3.2 Discussion of necessary enforcement activity

As noted above, the primary difference between enforcing an emissions trading program with permit banking and one without lies in deterring the incentive of a firm under a banking regime to under-report its emissions in order to save additional permits for the future. The strategies of [9] and [10] suggest that enforcing a program with banking calls for a more stringent policy in a particular sense. Note that in all periods but the last, cost-effective monitoring without a banking option calls for choosing $\pi_t = p_t /[\, g'(0) + f'(0) + \beta p_{t+1}]$, while cost-effective monitoring with banking calls for $\pi_t = p_t /[\, g'(0) + \beta p_{t+1}]$. Because $p_t /[\, g'(0) + f'(0) + \beta p_{t+1}] < p_t /[\, g'(0) + \beta p_{t+1}]$, the monitoring strategy that is effective in deterring reporting violations in the absence of banking would not be effective if applied to a program with banking—the strategy provides insufficient monitoring for a program with banking. On the other hand, the effective monitoring strategy for deterring reporting violations when banking is allowed would be more than sufficient (albeit more costly) to deter reporting violations in a program without banking.

This is not to say that more monitoring effort must be applied to permit trading programs with banking than to programs without banking, because permit prices under the two regimes will evolve differently. We will examine the relative monitoring requirements of banking and non-banking systems in the next section.

Note from [9] and [10] that the self-reporting penalty $g(\cdot)$ is not necessary to deter reporting violations when banking is prohibited, nor in the last period of the banking and non-banking regimes. In these cases the reporting penalty and the penalty for permit violations are perfect substitutes for each other. This is true because the only motivation for under-reporting in these cases is to conceal a permit violation, and if this is discovered, both violations are penalized. Therefore, truthful emissions reporting can be induced without a self-reporting penalty as long as the marginal penalty for emissions violations, $f'(\cdot)$, is sufficiently high. However, the self-reporting penalty can play a sort of supporting role in the sense that its application can be used to reduce the amount of monitoring necessary to induce truthful emissions reporting.

On the other hand, the self-reporting penalty plays a critical role in the enforcement of emissions trading programs with bankable permits. In all but the last period, only the self-reporting penalty shows up in the strategy to deter reporting violations.

Our results about the role of the reporting penalty have clear policy implications that run contrary to actual practice. Emissions monitoring in both the SO_2 and RECLAIM programs rely heavily on emissions data generated and reported by the facilities themselves. We find that a reporting penalty is necessary to deter reporting violations when permits can be banked.

However, despite the importance of permit banking in the SO_2 program there are no explicit provisions for penalizing reporting violations. Instead facilities under the SO_2 program face very stringent technological and process requirements for monitoring emissions and submitting emissions reports to the EPA that appear to be designed to minimize the opportunities for submitting false emissions data [Stranlund, Chavez, and Field (2002)]. Interestingly, even though our analysis suggests that reporting penalties in trading programs that prohibit permit banking serve only a supporting role, facilities in the RECLAIM program, which does not allow permit banking, can be penalized for submitting false emissions reports.[13]

To complete this section we compare our results about enforcing dynamic emissions trading programs with the results from the static case derived by Stranlund and Chavez (2000). The enforcement strategy in the static case is the same as the last period strategy in the dynamic context. In a static context, truthful emissions reporting is guaranteed if $p \leq \pi[g'(0) + f'(0)]$. Given truthful emissions reporting, a firm is permit complaint if and only if $p \leq f'(0)$.

Stranlund and Chavez (2000) note that if the penalty schedules are applied uniformly to all firms and permits are traded competitively so that all firms face the same permit price, there is nothing specific about individual firms that is required to set the appropriate enforcement strategy. This implies that, given the trivial requirement that the enforcer knows the penalty functions, the enforcer need only observe the prevailing permit price. Information about individual firms—their production or emissions-control technologies, their abatement costs more generally, or any other firm-specific information for that matter—is simply not useful to

[13] Rule 2004, subsection (e)-(1) of the RECLAIM regulations prohibits submission of inaccurate emissions reports and makes such a submission a violation of Rule 2004. Rule 2010, subsection (c) specifies maximum financial penalties for *any* violation of RECLAIM regulations. As in the SO_2 program, RECLAIM facilities also face rather stringent technological requirements for monitoring and reporting emissions. RECLAIM regulations are available at http://www.aqmd.gov/rules/html/tofc20.html.

the enforcer. Furthermore, since nothing distinguishes the compliance incentives of competitive firms in emissions trading programs, there is no reason for an enforcer to contemplate a targeted enforcement strategy. That is, provided that penalties are applied uniformly, the firms should be monitored with the same probability.[14]

In the dynamic context, whether or not permit banking is an option, information about the firms' abatement costs is not useful to the regulator. One obvious difference between the static and dynamic cases is that the offset penalty—the deduction from next period's allocation for a compliance problem in this period—is available in all periods of the dynamic cases but the last. This penalty provides an additional deterrent against non-compliance, because firms will account for the present value of a lost permit in the future when making their current compliance decisions. In contrast to the static case, therefore, firms' compliance incentives in the dynamic case may differ if they use different discount rates or form different beliefs about how permit prices will evolve. Otherwise they face the same compliance incentives and, as in the static case, there is no justification for applying different levels of monitoring effort to different firms.

Lastly, an effective enforcement strategy in the static case does not require a penalty for reporting violations; accurate emissions reporting and complete emissions compliance can be achieved with only the penalty for permit violations. We have shown that the reporting penalty plays a critical role in enforcing a dynamic trading program with banking, but is not necessary when banking is prohibited.

[14] Enforcement to guarantee full compliance with emission standards is quite different. Information about firms' marginal abatement costs becomes relevant; in fact, firms with higher marginal abatement costs should be monitored more closely, because their incentives for non-compliance are greater [Garvie and Keeler (1994)].

4. Relative monitoring effort in emissions trading programs with and without banking

We have argued that deterring non-compliance in an emissions trading program with banking requires a more stringent enforcement strategy than if banking was prohibited, but this does not directly imply that more enforcement effort is required when permits can be banked. To examine whether more enforcement effort is required when firms can bank emissions permits we must examine the evolution of permit prices under the two regimes. To date, Schennach (2000) has provided the most complete analysis of the time paths of aggregate emissions and permit prices in trading programs with banking. In this section we combine some of her results with our enforcement strategies [9] and [10] to examine relative enforcement requirements for two emissions trading programs that are identical except that one allows permit banking while the other does not. Because our enforcement strategies induce full compliance, no penalties are collected, and the only enforcement effort expended is monitoring effort.

In Schennach's analysis, the industry faces an aggregate emissions standard that is relatively high in the first phase of an emissions trading program, but then is reduced in the second phase. The solid line in the top panel of Figure 1 illustrates the aggregate standard, which jumps down in period $\bar{t}$. With an enforcement strategy that induces full compliance, this path also represents aggregate demand for permits when permits cannot be banked. Assuming that abatement cost functions and discount rates do not change over time, the solid line in the bottom panel of Figure 1 (labeled p_t^{nb}) illustrates the path of equilibrium permit prices when permit banking is prohibited.

In a program that allows banking, facilities will save permits during the first phase of the program to smooth out the decrease in the aggregate standard. At some point during the second phase, say $\bar{\bar{t}}$, the permit bank will be exhausted. Thereafter, since enforcement induces full compliance, facilities will hold their emissions to the aggregate standard imposed in the second phase. The dashed path in the top panel of Figure 1 illustrates the evolution of aggregate emissions when banking is allowed.

The dashed path in the bottom panel of Figure 1, labeled p_t^b, illustrates how nominal permit prices evolve when permits can be banked. A fundamental result from the literature on dynamic emissions trading is that equilibrium prices of bankable permits must rise with the rate of discount when firms are actually banking permits [Cronshaw and Kruse (1996), Rubin (1996), Kling and Rubin (1997), and Schennach (2000)]. In Figure 1, $p_t^b = \beta\, p_{t+1}^b$ for $t = 0, \ldots, \bar{\bar{t}} - 1$. During the interval (0, $\bar{t}$ - 1), facilities are holding their emissions below the aggregate standard in order to save permits for the future. This implies that the prices of bankable permits in this interval are higher than the price that would prevail if banking was prohibited.[15] At $\bar{t}$ when the aggregate emissions standard is reduced, the permit price in the non-banking program jumps up above the prices that would prevail with bankable permits. At $\bar{\bar{t}}$, when the permit bank in the banking program is exhausted, p_t^b reaches the price that prevails under the non-banking program and remains at this level as facilities meet the aggregate standard of the second phase thereafter.

The preceding discussion suggests three basic relationships between equilibrium permit prices for programs that are identical except that one allows permit banking while the other does not. (1) Firms are banking permits in the program that allows them to do so, and equilibrium

[15] A brief explanation may be in order here. Recall that in each period, a firm chooses its emissions to equate its marginal abatement costs to the prevailing permit price [Proposition 1]. In the usual manner, one can use this fact to construct an aggregate marginal abatement cost function, $-C'(E_t)$, where E_t is aggregate emissions in t. It is straightforward to show that if all individual abatement cost functions are strictly convex, $-C'(E_t)$ is decreasing in E_t. As long as enforcement induces full compliance so that aggregate demand for permits in t is exactly equal to aggregate emissions, the equilibrium permit price is determined by $p_t = -C'(E_t)$, which implies that the permit price is decreasing in aggregate emissions. Since, during (0, $\bar{t}$ - 1), aggregate emissions are lower when banking is allowed than when banking is not allowed, $p_t^b > p_t^{nb}$.

permit prices are higher than the price that would prevail in the non-banking program. (2) Firms are banking permits in the banking program, but permit prices are lower than the price that would prevail if banking was prohibited. In both of these cases, real permit prices under the banking regime are constant; that is, $p_t^b = \beta\, p_{t+1}^b$ for $t = 0, \ldots, \bar{\bar{t}} - 1$. (3) Firms in the banking program are choosing not to bank permits, which implies that the equilibrium permit price is the same under both programs.

To examine the relative monitoring requirements to achieve complete compliance for each of these cases, let us assume that monitoring levels are set as low as possible, but just high enough to ensure compliance. From [9] and [10], cost-effective monitoring in all but the last period requires

$$\pi_t^b = p_t^b / [\, g'(0) + \beta\, p_{t+1}^b \,] \text{ and } \pi_t^{nb} = p_t^{nb} / [\, g'(0) + f'(0) + \beta\, p_{t+1}^{nb} \,],\ t = 0, \ldots, T-1, \qquad [11]$$

under the banking and non-banking programs, respectively. Note from [9] and [10] that the strategies for choosing monitoring levels in the last period of both programs are the same. Furthermore, since permit prices under both programs must be the same in the last period, minimal monitoring levels must be equal in the last period of both programs.

As for penalties, the strategies [9] and [10] require that the penalty for a slight permit violation, $f'(0)$, must be greater than or equal to the equilibrium permit price that prevails in the last period ($f'(0) \geq p_T$). From Figure 1, this price is the same under both programs, and the prices in all previous periods of both programs are less than or equal to this price. Therefore, $f'(0) \geq p_t^b$ and $f'(0) \geq p_t^{nb}$, $t = 0, \ldots, T$.

We are now ready to examine how monitoring requirements are different under the two programs for the three cases of relative equilibrium permit prices described above. The following proposition is proved in the appendix.

Proposition 6**:** *For two emissions trading programs that are identical except that one allows permit banking while the other does not, in all periods but the last:*

(1) *If firms are banking permits and permit prices are higher than the price that would prevail if banking was prohibited, monitoring levels must be higher in the banking program than in the non-banking program.*

(2) *If firms are banking permits and permit prices are below the price that would prevail if banking was prohibited, then* $sign[\pi_t^b - \pi_t^{nb}] = sign[p_t^b - \overline{p}_t^b]$, *where* $\overline{p}_t^b$ = $p_t^{nb} g'(0) / [g'(0) + f'(0) - p_t^{nb} + \beta p_{t+1}^{nb}] < p_t^{nb}$.

(3) *If firms are allowed to bank permits but are not doing so, monitoring levels must be higher in the banking program than in the non-banking program.*

Proposition 6 makes it clear that the only time monitoring levels under a banking program may be less than in the non-banking program is when permits prices in the banking program are significantly lower than the price that would prevail in the non-banking program. Referring to the price paths in Figure 1, in the initial time interval (0, $\overline{t}$ -1) prices of bankable permits are higher than the price that would result if banking was prohibited. Consequently, required monitoring levels in the banking program are higher in the initial interval than in the program that prohibits permit banking.

In the third time interval, $\overline{\overline{t}}$ to T, in which the permit bank has been exhausted and firms under both programs simply meet the more stringent aggregate standard in every remaining period, the equilibrium permit price is the same under both programs. However, since allowing permit banking requires a more stringent enforcement strategy whether firms bank permits or not, more monitoring is required in this interval for the banking program than is required when banking is prohibited.

It is only in the middle time interval that monitoring levels under the banking program may fall below what would be required in the absence of banking. At $\overline{t}$ when the permit price in the non-banking program jumps up above the prices in the banking program in response to the lower aggregate emissions standard, if the price in the banking program is far enough below the price that would prevail without banking, monitoring in the banking program may fall below what is required in the non-banking program. Eventually though, as prices in the banking program rise through this interval, monitoring must once again rise above the level that is required in the absence of banking. Furthermore, it is possible that the difference between the banking and non-banking prices at $\overline{t}$ is not large enough to allow monitoring levels in the banking program to fall below what is required in the non-banking program. If this is the case, monitoring levels must be higher in the banking program throughout this middle interval of time, and indeed, throughout the life of the program.

5. Conclusion

We have addressed a fundamental policy question about emissions trading programs that allow firms to bank emissions permits for future use or sale: Does allowing permit banking call for a different enforcement strategy? We have shown that compliance incentives and the enforcement strategies necessary to deter non-compliance are different in emissions trading programs that allow permit banking than in programs that prohibit banking, primarily because firms that can bank permits have an incentive to under-report their emissions in order to save additional permits for the future. Consequently, the enforcement strategy that deters non-compliance cost-effectively in a trading program with banking is more demanding than what is required when banking is prohibited, in the sense that the appropriate enforcement strategy for a program without banking would not deter all non-compliance if it were applied to a program with bankable permits. Put another way, given identical prices in trading programs with and without permit banking, more monitoring effort must be expended in the program with bankable permits.

But, of course, permit prices will evolve differently in trading programs with permit banking than in programs that prohibit banking. By combining our results about effective enforcement with a model of the evolution of permit prices, we have shown that emissions trading with bankable permits requires higher monitoring levels, except if equilibrium permit prices fall significantly below the prices that would prevail if permits could not be banked.

To accomplish the objective of this work, we constructed a model that is, to our knowledge, the first model of compliance and enforcement of dynamic emissions trading programs. Moving from static models of compliance and enforcement to dynamic environments opens up several avenues for further research, in particular other opportunities for structuring enforcement strategies. For example, one may examine the consequences of being able to check records for past compliance in addition to checking for current compliance. Then, a firm's expectation of whether a current violation will be discovered will be based not only on the probability that it will be audited in the current period, but also on the probability that it is audited in the future. We expect that the ability of an enforcer to revisit past compliance records would serve as additional source of deterrence.

One may also examine so-called state-dependent enforcement strategies for emissions trading programs. Such a strategy may involve monitoring a firm more closely if it has had a compliance problem in the past. Harrington (1988) has examined this type of strategy in the enforcement of standards, and found that the possibility of being monitored more closely in the future provides additional deterrence in the present. It is not clear what role state-dependent strategies may play in enforcing emissions trading programs, but we think it is a worthwhile issue to pursue.

One may also investigate different modes of penalizing non-compliance. Although sanctions for permit violations in the RECLAIM and SO_2 programs, as well as in our model, include a requirement that permits be deducted from future allocations to cover a current permit violation, these offsets probably have limited deterrence value because they are done on a one-to-one basis. Alternatively, sanctions in the EPA's NO_X Budget Program are based on offset penalties that are done on a three-to-one basis [see OTC NOx Budget Model Rule, http://www.epa.gov/airmarkets/otc/index.html]. Since regulatory authorities have shown a preference for offset penalties over financial sanctions in at least one emissions trading program, it may be worthwhile to adapt the model of this paper to examine the application of offset penalties in a rigorous fashion.

In general, continuing to extend the theoretical foundations of designing and managing emissions trading programs to dynamic environments will probably reveal ways in which regulatory authorities can manage these programs more effectively.

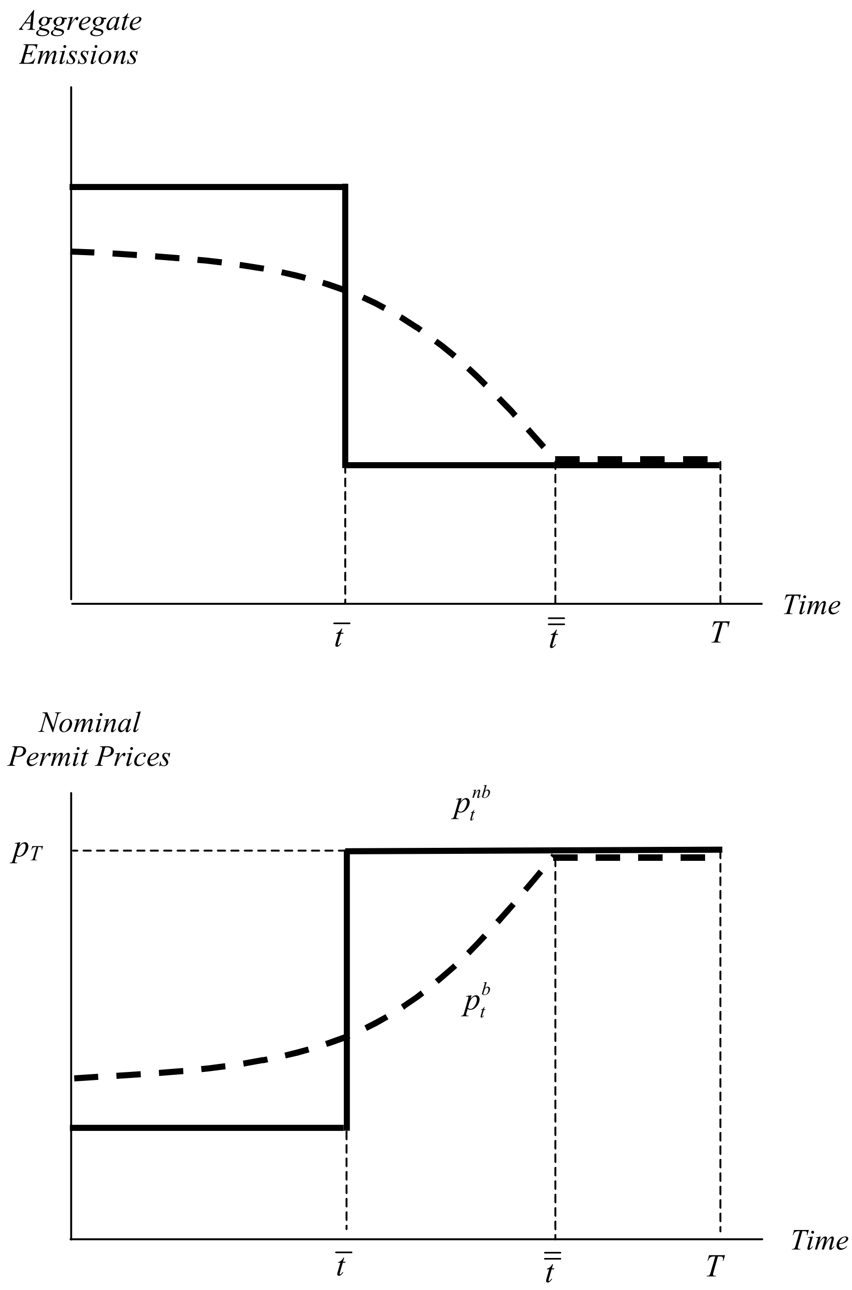

Figure 1: Time paths of aggregate emissions and nominal permit prices.

Appendix

Proof of Lemma 1: To prove the desired result, we require the following two lemmas:

Lemma 2: For all periods s for which the firm is perfectly compliant, if $J_{s+1}(x_{s+1}) = -p_{s+1}x_{s+1} + C_{s+1}$, then $J_s(x_s) = -p_s x_s + C_s$, for some constants C_{s+1} and C_s.

Proof of Lemma 2: Full compliance in period s implies that no penalties are collected in this period. Therefore, using [1],

$$v(e_s, l_s, r_s, x_s) = c(e_s) + p_s l_s. \qquad \text{[A.1]}$$

Furthermore, truthful reporting in s ($r_s = e_s$) implies from the state equation [2] that

$$x_{s+1} = \overline{l}_{s+1} + x_s + l_s - e_s. \qquad \text{[A.2]}$$

Note that x_{s+1} is deterministic, which implies that $J_{s+1}(x_{s+1})$ is also deterministic. Using this fact, the assumption that $J_{s+1}(x_{s+1}) = -p_{s+1}x_{s+1} + C_{s+1}$, [A.1], and [A.2], the period s value function is

$$\begin{aligned} J_s(x_s) &= \min_{e_s, l_s} \; c(e_s) + p_s l_s + \beta J_{s+1}(x_{s+1}) \\ &= \min_{e_s, l_s} \; c(e_s) + p_s l_s - \beta p_{s+1}(\overline{l}_{s+1} + x_s + l_s - e_s) + C_{s+1}. \end{aligned} \qquad \text{[A.3]}$$

Note that $J_s(x_s)$ is linear in l_s, which implies that in general l_s is indeterminate. However, using equation [5], permit compliance in s implies $l_s = e_s - x_s + a_s$. Substitute this into [A.3] and rearrange terms to obtain

$$J_s(x_s) = \min_{e_s} \; c(e_s) + p_s(e_s - x_s) + \textit{constant}. \qquad \text{[A.4]}$$

The optimal choice of e_s is uniquely determined by $c'(e_s) + p_s = 0$. Substituting the optimal e_s into [A.4] yields $J_s(x_s) = -p_s x_s + C_s$, for some constant C_s, which is the desired result. QED

Lemma 3: The final period value function is $J_T(x_T) = -p_T x_T + C_T$, and by induction, $J_j(x_j) = -p_j x_j + C_j$, for some constants C_j, $j = t + 1, \ldots, T$.

***Proof of Lemma 3*:** Given perfect compliance in T and $J_{T+1}(x_{T+1}) = 0$, we have $J_T(x_T) = \min_{e_T, l_T} c(e_T) + p_T l_T$. Permit compliance in T implies $l_T = e_T - x_T$ and $J_T(x_T) = \min_{e_T} c(e_T) + p_T(e_T - x_T)$. Upon substitution of the optimal e_T, derived from $c'(e_T) + p_T = 0$, we have $J_T(x_T) = -p_T x_T + C_T$. Using Lemma 2, by induction the period $T-1$, $T-2$, … , $t+1$ value functions take the same form, which is the desired result. QED.

From Lemma 3, $J_{t+1}(x_{t+1}) = -p_{t+1}x_{t+1} + C$, for some constant C. From the perspective of possibly non-compliant period t choices, $E_t[J_{t+1}(x_{t+1})] = -p_{t+1}E_t(x_{t+1}) + C$, which completes the proof of Lemma 1. QED.

Proof* of *Proposition 1: Combine [8-a], [8-b], and [8-c] to obtain the result for $t \neq T$. For the last period consult Stranlund and Chavez (2000). QED.

Proof of Proposition 2: If the firm is permit compliant ($e_t = x_t + l_t$) it will choose $r_t = e_t$, because under-reporting its emissions when it is permit compliant is inconsistent with the prohibition on permit banking. That is, permit compliance, $e_t = x_t + l_t$, and under-reported emissions, $r_t < e_t$, imply $r_t < x_t + l_t$, which violates the no-banking constraint $r_t \geq x_t + l_t$.

We now show that $p_t \leq \pi_t[g'(0) + f'(0) + \beta p_{t+1}]$ is sufficient to guarantee truthful emissions reports from the firm when it is not permit compliant in any period but the last. First, let us suppose that [8-b] holds so that permit transactions are chosen optimally. Note that [8-b] implies

$$(1-\pi_t)f'(r_t - (x_t + l_t)) + \beta p_{t+1} - \gamma_t = p_t - \pi_t f'(e_t - (x_t + l_t)). \quad \text{[A.5]}$$

Furthermore, [8-c] can be rewritten as $\partial\theta_t/\partial r_t = (1-\pi_t)f'(r_t - (x_t + l_t)) + \beta p_{t+1} - \gamma_t - \pi_t g'(e_t - r_t) - \pi_t \beta p_{t+1} + \mu_t = 0$. Substitute [A.5] into $\partial\theta_t/\partial r_t$ to obtain

$$\partial\theta_t/\partial r_t = p_t - \pi_t\,[g'(e_t - r_t) + f'(e_t - (x_t + l_t)) + \beta p_{t+1}] + \mu_t = 0. \quad \text{[A.6]}$$

To show that $p_t \leq \pi_t [g'(0) + f'(0) + \beta p_{t+1}]$ is sufficient to guarantee $r_t = e_t$ when the firm is not permit compliant, suppose toward a contradiction that $p_t \leq \pi_t [g'(0) + f'(0) + \beta p_{t+1}]$, and $e_t - (x_t + l_t) > 0$, but that $r_t < e_t$. From [8-d], $r_t < e_t$ implies $\mu_t = 0$. Furthermore, because the penalty functions are strictly convex, $r_t < e_t$ implies $g'(e_t - r_t) > g'(0)$, and $e_t - (x_t + l_t) > 0$ implies $f'(e_t - (x_t + l_t)) > f'(0)$. These inequalities and $\mu_t = 0$ imply $\partial\theta_t/\partial r_t = p_t - \pi_t [g'(e_t - r_t) + f'(e_t - (x_t + l_t)) + \beta p_{t+1}] < 0$, which contradicts [A.6]. QED.

Proof of Proposition 3: Suppose that permit transactions are chosen optimally. Then, as in the previous proof, an optimal report is characterized by [A.6]. However, if the firm is permit compliant, $e_t \leq (x_t + l_t)$, $f(e_t - (x_t + l_t)) = 0$, and we evaluate $f'(e_t - (x_t + l_t))$ at $f'_-(0) = 0$. Therefore, an optimal emissions report must satisfy

$$\partial\theta_t/\partial r_t = p_t - \pi_t [g'(e_t - r_t) + \beta p_{t+1}] + \mu_t = 0. \qquad \text{[A.7]}$$

Suppose that the firm contemplates a reporting violation $e_t - r_t = \alpha > 0$. From [8-d], $e_t - r_t > 0$ implies $\mu_t = 0$. Therefore, using [A.7], if this reporting violation is optimal,

$$\partial\theta_t/\partial r_t = p_t - \pi_t [g'(\alpha) + \beta p_{t+1}] = 0. \qquad \text{[A.8]}$$

The necessity of $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$ in eliciting a truthful report in this setting follows because $p_t > \pi_t [g'(0) + \beta p_{t+1}]$ cannot deter an arbitrarily small reporting violation. That is, with $p_t > \pi_t [g'(0) + \beta p_{t+1}]$ and letting α approach zero, we have $\lim_{\alpha\to 0} \partial\theta_t/\partial r_t = p_t - \pi_t [g'(0) + \beta p_{t+1}] > 0$, which contradicts [A.8].

To show that $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$ is also sufficient to guarantee $r_t = e_t$, suppose toward another contradiction that $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$, but $e_t - r_t = \alpha > 0$. As above, if this reporting violation is optimal, [A.8] holds. However, since g is strictly convex, $g'(\alpha) > g'(0)$. Thus, if $p_t \leq \pi_t [g'(0) + \beta p_{t+1}]$, $\partial\theta_t/\partial r_t = p_t - \pi_t [g'(\alpha) + \beta p_{t+1}] < 0$, which contradicts [A.8]. QED.

Proof of Proposition 4: The proof proceeds in exactly the same way as that part of the proof of Proposition 2 that establishes the sufficiency of $p_t \leq \pi_t[g'(0) + f'(0) + \beta p_{t+1}]$ in deterring a reporting violation by a firm that is not permit compliant when banking is prohibited. QED.

Proof of Proposition 5: Given truthful emissions reporting, from [8-b] the firm's optimal demand for permits is

$$\partial\theta_t/\partial l_t = p_t - f'(e_t - (x_t + l_t)) - \beta p_{t+1} + \gamma_t = 0. \qquad \text{[A.9]}$$

Suppose that the firm contemplates a permit violation $e_t - (x_t + l_t) = \eta > 0$. Since $r_t = e_t$, $r_t - (x_t + l_t) = \eta > 0$. From [8-e], $-(r_t - (x_t + l_t) + b) = -\eta - b < 0$, implies $\gamma_t = 0$. Using [A.9], if the permit violation η is optimal,

$$\partial\theta_t/\partial l_t = p_t - f'(\eta) - \beta p_{t+1} = 0. \qquad \text{[A.10]}$$

The necessity of $p_t \leq f'(0) + \beta p_{t+1}$ in deterring a permit violation with truthful emissions reporting follows from the fact that $p_t > f'(0) + \beta p_{t+1}$ cannot deter an arbitrarily small permit violation. With $p_t > f'(0) + \beta p_{t+1}$ and letting η go to zero, we have $lim_{\eta\to 0}\partial\theta_t/\partial l_t = p_t - f'(0) - \beta p_{t+1} > 0$, which contradicts [A.10].

To establish sufficiency, suppose toward another contradiction that $p_t \leq f'(0) + \beta p_{t+1}$, but $e_t - (x_t + l_t) = \eta > 0$. Again, if this violation is optimal, [A.10] holds. However, since f is strictly convex, $f'(\eta) > f'(0)$. Thus, if $p_t \leq f'(0) + \beta p_{t+1}$, $\partial\theta_t/\partial l_t = p_t - f'(\eta) - \beta p_{t+1} < 0$, which contradicts [A.10]. For the last period result consult Stranlund and Chavez (2000).QED

***Proof of Proposition 6*:** Relative monitoring levels in all periods but the last are determined by subtracting π_t^{nb} from π_t^{b}. Using [11]

$$sign[\pi_t^b - \pi_t^{nb}] = sign[G = p_t^b(g'(0) + f'(0) + \beta p_{t+1}^{nb}) - p_t^{nb}(g'(0) + \beta p_{t+1}^{b})]. \qquad \text{[A.11]}$$

For case (1), since firms that are allowed to bank permit are doing so, $p_t^b = \beta\, p_{t+1}^b$ and

$$G = p_t^b\,[g'(0) + f'(0) + \beta\, p_{t+1}^{nb}\,] - p_t^{nb}\,[g'(0) + p_t^b\,]$$
$$= g'(0)[\,p_t^b - p_t^{nb}\,] + p_t^b\,[\,f'(0) - p_t^{nb} + \beta\, p_{t+1}^{nb}\,]. \qquad [A.12]$$

Both terms of [A.12] are positive because $p_t^b > p_t^{nb}$ and $f'(0) \geq p_t^{nb}$. Therefore, *G* is positive and for case (1), $\pi_t^b > \pi_t^{nb}$.

Let us skip ahead to case (3). If firms that are allowed to bank permits are not doing so, permit prices under the two programs must be equal. Since $p_t^b = p_t^{nb}$,

$$G = p_t^b\,[g'(0) + f'(0) + \beta\, p_{t+1}^b\,] - p_t^b\,[g'(0) + \beta\, p_{t+1}^b\,] = p_t^b f'(0) > 0.$$

Since *G* is positive in this case, $\pi_t^b > \pi_t^{nb}$.

Case (2) is not as straightforward as the others, because nominal prices with banking are below the price that prevails without banking. Since firms that are allowed to bank permits are doing so, $p_t^b = \beta\, p_{t+1}^b$. Therefore,

$$G = p_t^b\,(g'(0) + f'(0) + \beta\, p_{t+1}^{nb}) - p_t^{nb}\,(g'(0) + p_t^b)$$
$$= p_t^b\,[\,g'(0) + f'(0) - p_t^{nb} + \beta\, p_{t+1}^{nb}\,] - p_t^{nb}\, g'(0) \qquad [A.13]$$

While the second term of [A.13] is negative, the first is positive because $f'(0) \geq p_t^{nb}$. However, it is easy to verify that [A.13] has the following characteristics: (*i*) $G(\,p_t^b = p_t^{nb}\,) > 0$; (*ii*) $G(\,p_t^b = 0) < 0$, and (*iii*) $\partial G/\partial\, p_t^b > 0$. These characteristics imply that there exists a price $\bar{p}_t^b < p_t^{nb}$ such that $G(\,\bar{p}_t^b\,) = 0$. This price is

$$\bar{p}_t^b = p_t^{nb} g'(0) \big/ [g'(0) + f'(0) - p_t^{nb} + \beta\, p_{t+1}^{nb}]\,. \qquad [A.14]$$

Since we require that $f'(0) \geq p_t^{nb}$, $g'(0) \big/ [g'(0) + f'(0) - p_t^{nb} + \beta p_{t+1}^{nb}] < 1$. Therefore, $\overline{p}_t^b$ must be less than p_t^{nb}. Furthermore, since *G* is strictly increasing in p_t^b, [A.13] and [A.14] imply *sign G* = *sign*(p_t^b - $\overline{p}_t^b$). Therefore, from [A.11], *sign*[π_t^b - π_t^{nb}] = *sign*[p_t^b - $\overline{p}_t^b$]. QED.

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