Should Emissions Permit Programs Allow Trading and Banking?

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Abstract

This paper develops a framework for evaluating the efficiency of bankable or tradable emissions permits relative to emissions taxes or quotas, when there is uncertainty in the regulator's knowledge of firms' costs. The model indicates that when abatement at one location is a perfect substitute for abatement at any other location, as in the case of a globally mixed pollutant, tradable permits dominate fixed emissions quotas. However, when pollution is highly localized, with marginal damages from a given pollution source being independent of pollution emissions from other sources, tradable permits are typically dominated either by taxes or quotas.

Analogous results apply for permit banking in a dynamic context. In the case of a flow pollutant, damages in one period depend only on emissions in that period, and thus bankable permits are typically dominated either by taxes or quotas. In contrast, for a stock pollutant, especially one with a low decay rate, abatement in any one period is a close substitute for abatement in other periods, and thus bankable permits are generally more efficient than quotas.

These results could have substantial importance for environmental policy. They strongly suggest that many current environmental regulations are not optimal. For example, emissions permit programs for flow pollutants typically allow banking (for example, the lead phase-out and sulfur dioxide permit programs), while the Kyoto agreement to reduce carbon dioxide emissions–a stock pollutant–does not allow for such intertemporal flexibility.

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I. Introduction

There has been a strong recent trend in US environmental policy toward the use of tradable emissions permit systems. While there has been substantial debate over many aspects of these programs, most economists support allowing firms to trade these emissions permits. There seems to be a similar consensus on the closely related question of whether firms should be allowed to bank or borrow permits–transactions that can be thought of as trades among different time periods rather than among different sources in the same time period.

These conclusions might come from the simple intuition that there will be gains from trade, or they might be based on studies of the cost-effectiveness of such systems. Montgomery (1972) found that a system of tradable permits can achieve any given emissions standard at the lowest cost. The analogous result that a system allowing banking and borrowing will achieve a given standard at the least present-value cost was shown by Cronshaw and Kruse (1996) in a discrete-time model, and by Rubin (1996) in a continuous-time model.

Recent policies have generally reflected this consensus. As noted above, many new regulatory programs use tradable permit systems, and nearly all of these allow permit banking.[1] Few, if any, regulatory programs allow permit borrowing, but this seems to be due to worries about the enforceability and credibility of such a policy (concerns that a firm would borrow large numbers of permits and then either exit the industry or lobby for an increased permit allocation), not to inherent efficiency problems with such intertemporal trades.

Prior studies have noted one caveat; if marginal pollution damages vary across locations or time periods, and regulations do not reflect that difference, then trading and banking[2] may lower the cost of regulation but also lower the benefit, and thus produce a smaller net gain. Montgomery (1972) and McGartland and Oates (1985) argued that when marginal damages vary by location, trading should not occur at a one-to-one ratio, but rather at a ratio that reflects the ratio of marginal

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[1] Prominent examples of programs that allow permit banking in some form include the sulfur dioxide trading program from the 1990 Clear Air Act Amendments, California's Low-Emission Vehicle Program, and the CAFE vehicle fuel-economy standards. The greenhouse gas emissions targets adopted under the recent Kyoto Protocol represent a notable exception, being fixed in each year with no allowance for banking or borrowing.

[2] For brevity, the term "banking" will be used from this point on to refer both to banking (emitting less pollution than the standard in one period in order to exceed the standard in a later period) and borrowing (emitting more pollution than the standard in one period and then paying back the difference by emitting less in a future period).

1

damages from emissions at the two locations. Kling and Rubin (1997) show a similar result for permit banking in regulation of a flow pollutant, and derive the optimal intertemporal trading ratios. Leiby and Rubin (2000) do the same for regulation of a stock pollutant. These studies all conclude that allowing trading and banking will maximize the net benefit of regulation, as long as such transactions are conducted at the right trading ratios.[3]

All of these prior studies, however, utilize models in which the regulator has perfect knowledge of firms' costs and of pollution damages. This is a significant omission, because, in the absence of uncertainty, banking and trading are unnecessary; the regulator can directly set the optimal level of emissions at each source in each period. The potential gain from allowing trading and banking arises because firms have better information about their costs than the regulator, and thus, when given proper incentives, may come closer to the optimal level of emissions than the regulator could. Therefore it seems clear that to determine the efficiency of banking and trading, one must use a model that incorporates uncertainty.

This paper develops such a model, which draws heavily on Weitzman's (1974) seminal study comparing price instruments and quantity instruments. It then uses this model to answer the questions of if and when emissions permit systems should allow trading and banking.

The paper shows that when abatement at one location is a close substitute for abatement at other locations–as in the case of a globally mixed pollutant–tradable permits are generally more efficient than emissions quotas. A similar result applies for bankable permits in the case of a long-lived stock pollutant, where abatement in one period is a close substitute for abatement in other periods.

On the other hand, when the marginal pollution damage from emissions at one location depends only on emissions at that location–implying that abatement is not substitutable across locations–tradable permits are typically dominated either by taxes or quotas. An analogous result applies for bankable permits in the case of a flow pollutant.

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[3] In practice, most emissions permit programs set the trading ratio one-to-one for trading or banking, though this is not universally the case. One exception is the California Low-Emission Vehicle Program, which sets the trading ratio such that banking one permit today allows less than one unit of emissions in future years. However, as Kling and Rubin (1997) note, this is the opposite of how the ratio should be set; since the discounted value of damages in the future is less than the value of damages today, banking one permit today should allow more than one unit of emissions in the future.

A key insight of the paper is that when abatement costs or pollution damages are uncertain, the optimal ratios for banking and trading will also generally be uncertain. Thus, even if those ratios are set optimally *ex ante*, it may not be optimal to allow trading and banking, because the trading or banking ratios will likely not be optimal *ex post*.

The important difference between the various cases considered in this paper is the linkage between marginal damages from sources in different locations or different time periods. In the case of a flow pollutant, marginal damages in a given period depend only on emissions in that period; similarly, for an entirely localized pollutant, marginal damages at a given location depend only on emissions at that location. Since the damages are not linked across locations or time periods, there is no gain from linking regulation across periods. In this case, tradable permits are generally dominated by either emissions taxes or quotas.

In contrast, for stock pollutants, marginal damages *are* linked between time periods, and for pollutants that are not entirely localized, damages are linked between locations. Therefore, in these cases, it may be efficient for regulation to be linked between periods or locations as well, and thus bankable or tradable permit systems may be the most efficient instrument.

The next section of the paper develops a model of pollution regulation for a group of pollution sources, derives expressions for the relative efficiency of the three instruments, and then considers the implications of these expressions in several illustrative special cases. The third section considers dynamic pollution problems–both for a stock pollutant and for a flow pollutant–and shows that the framework developed in this paper can also be used to analyze permit banking in these cases. The final section offers conclusions and suggestions for future research.

II. The Model

This section develops a simple model of regulation of a group of pollution sources, and uses that model to investigate the relative efficiency of three regulatory instruments: an emissions tax, (non-tradable) emissions quotas, and tradable permits. The general structure of this model is similar to the model in Weitzman (1974), but differs in two important respects. First, this model considers tradable permits in addition to taxes and quotas. Second, this model's representation of

pollution damages is much more general, allowing for cases in which the effects of pollution are not identical across sources.

A. Assumptions

A set of pollution sources is assumed, distinguished by location, time period, or both. The total cost of emissions reduction over all sources is given by $C(q, \theta)$, where q is the vector of abatement (reductions in emissions from a baseline level) at each of the pollution sources[4] and θ is a vector of random variables. The total external benefit from emissions reductions is given by $B(q)$.[5] Both $C()$ and $B()$ are assumed to be continuous and twice-differentiable. It is also assumed that

$$E\left(\partial C/\partial q_i\right) \geq 0, \ E\left(\partial^2 C/\partial q_i^2\right) > 0, \ E\left(\partial^2 C/\partial q_i \partial q_j\right) \geq 0, \ E\left(\partial B/\partial q_i\right) \geq 0, \ E\left(\partial^2 B/\partial q_i^2\right) < 0,$$

$E\left(\partial^2 B/\partial q_i \partial q_j\right) \leq 0$ for all i and j, and that $E\left(\partial C/\partial q_i\right) > E\left(\partial B/\partial q_i\right)$ for q_i sufficiently large. Firms are assumed to set the level of abatement at each source to minimize abatement costs, subject to any regulatory constraints.[6] In the absence of regulation, then, emissions will be set such that the marginal cost of abatement is zero. Without loss of generality, we define the baseline level of emissions as the expected level of emissions in the absence of regulation, which implies

$$(1) \qquad E\left[\frac{\partial C}{\partial q_i}\right]\bigg|_{q=0} = 0$$

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[4] For consistency with prior work, especially Weitzman (1974), this model considers the effects of abatement, rather than emissions. Since abatement is just a constant minus emissions, this is purely a notational issue, and has no effect on the paper's results.

[5] For simplicity, we ignore uncertainty in the benefits of abatement. Weitzman (1974) showed that such uncertainty has no effect on the choice between price and quantity regulation, though Stavins (1996) pointed out that this is true only if the cost shocks are uncorrelated with the benefit shocks. These results also hold in the model considered in this paper.

[6] Since firms minimize costs, the cost function could be more accurately described as including all effects of abatement that are internalized by the firm in the absence of regulation. Similarly, the benefit function could be more accurately described as representing the effects that are external to the firm. Thus, cost spillovers that are not internalized would appear in the benefit function, while benefits of abatement that are internalized by the firm would appear as negative costs in the cost function.

The regulator can choose one of three regulatory instruments–a set of emissions taxes, a set of emissions quotas, or a system of tradable emissions permits.[7] Firms will set the level of abatement at each source to minimize abatement costs, subject to meeting the regulatory constraint. While the regulator does not know the realization of   when setting the regulation, firms do know the realization of   when choosing their level of emissions. For the emissions taxes, this implies the first-order condition

(2) $$\frac{\partial C}{\partial q_i} = \tau_i$$

where   is the vector of tax rates set by the regulator. Under the set of emissions quotas, firms have no choice about their emissions, which are simply equal to the quota.

(3) $$q_i = \bar{q}_i$$

where $\bar{q}$ is the vector of emissions quotas set by the regulator.

Under the system of tradable permits, the first-order condition is

(4) $$\frac{\partial C}{\partial q_i} = r_i$$

and the permit-market clearing condition is

(5) $$\sum_i r_i q_i = \tilde{q}$$

where r is the vector of trading rates (with one unit of emissions at source i requiring r_i emissions permits),   is the market price of an emissions permit, and $\tilde{q}$ is the total quantity of permits issued. Note that r and $\tilde{q}$ are set by the regulator, while   will be determined by the market.

The goal of the regulator is to maximize the expected value of benefits minus costs $E\big[B(q) - C(q, \cdot)\big]$.[8] This implies that $\bar{q}$ will be set so as to satisfy the first-order condition

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[7] Several papers have suggested more complex regulatory instruments that will generally be more efficient than the simple instruments considered here. For a recent example, see Kaplow and Shavell (1997). However, in practice, those more complex instruments are rarely used, and so this paper focuses only on the simple versions of these instruments.

[8] Note that distributional or other considerations could potentially be incorporated into the benefit and cost functions, so the assumption that the regulator maximizes benefits minus costs does not necessarily imply that the regulator is concerned only with economic efficiency.

(6) $\qquad E\left.\dfrac{\partial C}{\partial q_i}\right|_{q=\bar{q}} = \left.\dfrac{\partial B}{\partial q_i}\right|_{q=\bar{q}}$

In the absence of uncertainty, all three instruments would be set to achieve this same optimum level of emissions. For the emissions taxes, this would require the regulator to set the emissions tax at each source such that the tax equals the marginal benefit of reduced emissions from that source.

(7) $\qquad \tau_i = \left.\dfrac{\partial B}{\partial q_i}\right|_{q=\bar{q}} = \left.\dfrac{\partial C}{\partial q_i}\right|_{q=\bar{q}}$

Under the system of tradable permits, the trading ratios would be set with the number of permits required per unit of emissions from a given source proportional to the marginal benefit of reduced emissions at that source

(8) $\qquad r_i = k\left.\dfrac{\partial B}{\partial q_i}\right|_{q=\bar{q}}$

where k is any non-zero constant. The total number of permits issued would be given by

(9) $\qquad \tilde{q} = \sum_i r_i\bar{q}_i$

Without uncertainty, then, it does not matter which regulatory instrument is used. With uncertainty, however, the three instruments will have different effects. In order to proceed further, we will assume that the uncertainty is sufficiently small to justify a second-order approximation for the cost and benefit functions in the neighborhood of $\bar{q}$, the amount of abatement that would occur under the optimal quota.

(10) $\quad C(q,\cdot) \approx C(\bar{q},\cdot) + \sum_i \big(c_i + \epsilon_i(\cdot)\big)\hat{q}_i + \dfrac{1}{2}\sum_i\sum_j \gamma_{ij}\hat{q}_i\hat{q}_j$

and

(11) $\quad B(q) \approx B(\bar{q}) + \sum_i b_i\hat{q}_i + \dfrac{1}{2}\sum_i\sum_j \beta_{ij}\hat{q}_i\hat{q}_j$

where $\hat{q}$ is the deviation of abatement from $\bar{q}$, given by

(12) $\qquad \hat{q}_i = q_i - \bar{q}_i$

c and γ are the expected values of the vector of first derivatives and the matrix of second derivatives of the cost function evaluated at the amount of abatement that would occur under the optimal quota.

(13) $\quad c_i = E\left[\dfrac{\partial C}{\partial q_i}\right]\Big|_{q=\bar{q}}$

(14) $\quad \gamma_{ij} = E\left[\dfrac{\partial^2 C}{\partial q_i\,\partial q_j}\right]\Big|_{q=\bar{q}}$

b and β are the corresponding vector of first derivatives and matrix of second derivatives for the benefit function, also evaluated at the amount of abatement that would occur under the optimal quota.

(15) $\quad b_i = \dfrac{\partial B}{\partial q_i}\Big|_{q=\bar{q}}$

(16) $\quad \beta_{ij} = \dfrac{\partial^2 B}{\partial q_i\,\partial q_j}\Big|_{q=\bar{q}}$

and $\epsilon_i(\theta)$ is a function that translates the vector of random variables θ into a vertical shift in the abatement cost curve for source i. The definition of c (13) implies that $\epsilon_i(\theta)$ has an expected value of zero.

(17) $\quad E\big(\epsilon_i(\theta)\big) = 0$

We will assume that the marginal cost of abatement at each source does not depend on the amount of abatement at any other source. This implies that

(18) $\quad \gamma_{ij} = 0 \quad \forall\, i \neq j$

Finally, we assume that that the distribution of $\epsilon_i(\theta)$ is independent across different pollution sources.[9]

B. Abatement Levels Under Different Instruments

Taking a derivative of the approximation to the cost function (10) and substituting in (18) gives an approximation to the marginal cost of abatement for source i.

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[9] These assumptions are not strictly necessary, but they greatly simplify the analysis. The conclusion of this paper contains a brief discussion of cases in which these assumptions may be violated, and of how this would alter the model's results.

$$(19) \quad \frac{\partial C}{\partial q_i} \approx c_i + \theta_i(\ ) + \theta_{ii}\hat{q}_i$$

Combining the approximation to the marginal abatement cost (19) with the first-order condition for the emissions tax and rearranging give an approximation for the quantity of abatement under the emissions tax

$$(20) \quad \hat{q}_i \approx \frac{\tau_i - c_i - \theta_i(\ )}{\theta_{ii}}$$

It can be shown (the derivation is contained in a separate mathematical appendix, available from the author) that the optimal tax rate is equal to b (the expected marginal benefit at quantity $\bar{q}$), which in turn is equal to c (the expected marginal cost of abatement at quantity $\bar{q}$). Thus,

$$(21) \quad \tau_i \approx b_i = c_i$$

Substituting (21) into (20) yields

$$(22) \quad \hat{q}_i^t \approx \frac{-\theta_i(\ )}{\theta_{ii}}$$

where $\hat{q}_i^t$ is the quantity of abatement that will result under the optimal emissions tax system.

A similar process yields an expression for the quantity of abatement under a system of tradable permits. Substituting the expression for the marginal cost of abatement (19) into the first-order condition for the tradable permit system (4) and rearranging yield

$$(23) \quad \hat{q}_i \approx \frac{r_i \lambda - c_i - \theta_i(\ )}{\theta_{ii}}$$

It can be shown that the optimal system of tradable permits will set r (the vector of trading ratios) to be proportional to b (the expected marginal benefit at quantity $\bar{q}$).

$$(24) \quad kr_i \approx b_i = c_i$$

where k is any positive constant.

It is optimal for the regulator to issue enough permits that there is no surplus or shortage of permits when abatement is equal to $\bar{q}$ (derivations of (24) and (25) are contained in a separate mathematical appendix, available from the author).

$$(25) \quad \tilde{q} = \sum_i r_i \bar{q}_i$$

Substituting (23), (24), and (25) into the permit-market clearing condition (5) and rearranging (using (12)) yield an expression for the equilibrium permit price under the optimal permit system

$$(26) \qquad 1 + \frac{b_i \quad _i(\ )}{_i \qquad _{ii}}$$

where is the slope of the market demand curve for emissions permits under the optimal permit system, given by

$$(27) \qquad = 1/ \quad \frac{b_i^2}{_i \quad _{ii}}$$

Substituting (26) into (23) yields

$$(28) \qquad \hat{q}_i^p \quad \frac{b_i}{_{ii}} \quad \frac{b_j \quad _j(\ )}{_j \quad _{jj}} - \frac{_i(\ )}{_{ii}}$$

where $\hat{q}_i^p$ is the quantity of abatement that will result under the optimal tradable permit system.

C. Comparative Advantages of Different Instruments

Following Weitzman (1974), we define the comparative advantage of one instrument over another as the difference between the two instruments of the expected value of benefits minus costs.[10] The comparative advantage of one of the other two instruments relative to emissions quotas is thus given by

$$(29) \qquad = E\big[\big(B(q) - C(q,\ )\big) - \big(B(\bar{q}) - C(\bar{q},\ )\big)\big]$$

Substituting the approximations to the cost and benefit functions (13) and (14) into (29) and simplifying, using (6) and (12) give

$$(30) \qquad E \quad - \quad _i \quad _i(\ )\hat{q}_i + \frac{1}{2} \quad _i \quad _j \big(\quad _{ij} - \quad _{ij}\big)\hat{q}_i\hat{q}_j$$

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[10] In calculating the comparative advantage of one instrument over another, the model assumes that the regulatory parameters–quota levels, tax rates, trading ratios, and the number of permits allocated–are set optimally *ex ante*. If the parameters for one or both instruments are not set optimally, this may change the relative efficiency of the two instruments.

Substituting the expression for the amount of abatement under the optimal emissions tax (22) into (30) and simplifying, using (18), give an expression for the comparative advantage of the tax relative to the quota.

$$(31) \qquad \Delta^{TQ} \approx \sum_i \frac{\sigma_i^2}{2\gamma_{ii}^2}\left(\gamma_{ii} + \beta_{ii}\right)$$

where σ_i^2 is the variance of the marginal abatement cost for source i at abatement $\bar{q}$, which is approximated by the variance of $\theta_i(\cdot)$

$$(32) \qquad \sigma_i^2 = E\left[\frac{\partial C}{\partial q_i}\bigg|_{q=\bar{q}} - E\left(\frac{\partial C}{\partial q_i}\bigg|_{q=\bar{q}}\right)\right]^2 \approx E\left[\theta_i(\cdot)^2\right]$$

Equation (31) corresponds to the expression for the comparative advantage of prices over quantities from Weitzman (1974) for the case with multiple firms. This expression implies taxes will dominate quotas when the average across sources of the slope of the marginal cost curve is greater than the average slope of the marginal benefit curve. Quotas will dominate taxes when the average marginal benefit curve is steeper. Taxes allow firms more flexibility, which reduces expected costs. This is especially important when marginal costs are very sensitive to the quantity of abatement. However, to the extent that marginal benefits are sensitive to the quantity of abatement, this flexibility reduces expected benefits.

Substituting the expression for the amount of abatement under the optimal permit system (28) into (30) and simplifying, using (18), give an expression for the comparative advantage of tradable permits relative to quotas.

$$(33) \qquad \Delta^{PQ} \approx \sum_i \frac{\sigma_i^2}{2\gamma_{ii}^2}\left(\gamma_{ii} + \beta_{ii} - 2b_i^2\right) + \sum_i\sum_j \frac{b_i b_j}{2\gamma_{ii}\gamma_{jj}}\left(\gamma_{ij} - \beta_{ij}\right)\left[\sum_k \frac{b_k^2 \sigma_k^2}{\gamma_{kk}^2} - \frac{\sigma_i^2}{\gamma_{ii}} - \frac{\sigma_j^2}{\gamma_{jj}}\right]$$

The first term in (33) bears some resemblance to the comparative advantage of taxes relative to quotas. This reflects the greater flexibility that firms have under tradable permits as compared to quotas. The second term reflects the interactions that occur between different sources through the market for emissions permits. This term is difficult to interpret in the general case, but it will be discussed at length in the illustrative special cases considered in the next section.

Finally, we can calculate the comparative advantage of tradable permits relative to emissions taxes. This is equal to the difference between the comparative advantage of tradable permits relative to emissions quotas and the comparative advantage of emissions taxes relative to emissions quotas.

$$(34) \qquad \Delta^{PT} = E\left[\left(B\!\left(q^p\right) - C\!\left(q^p,\ \theta\right)\right) - \left(B\!\left(q^t\right) - C\!\left(q^t,\ \theta\right)\right)\right] = \Delta^{PQ} - \Delta^{TQ}$$

Substituting the expressions for Δ^{TQ} (31) and Δ^{PQ} (33) into (34) and simplifying give

$$(35) \qquad \Delta^{PT} = \sum_i \frac{\sigma_i^2}{2\gamma_{ii}^2}\left(-2b_i^2\ \right) + \sum_i\sum_j \frac{b_i b_j}{2\gamma_{ii}\gamma_{jj}}\left(\sigma_{ij} - \phi_{ij}\right)\left[\sum_k \frac{b_k^2\sigma_k^2}{\gamma_{kk}^2} - \frac{\sigma_i^2}{\gamma_{ii}} - \frac{\sigma_j^2}{\gamma_{jj}}\right]$$

D. Interpreting the Comparative Advantage Formulas

To clarify the relative merits of the different regulatory instruments, this section consider several illustrative special cases.

i. When Abatement is Perfectly Substitutable Across Pollution Sources

The first special case comes when the benefits of reduced emissions take the form

$$(36) \qquad B(q) = B\left(\sum_i K_i q_i\right)$$

where K is a vector of constants. If all elements of K are equal, then this benefit function represents homogeneous emissions. If not, then the marginal benefit from abatement will vary across the different sources, but the ratio of marginal benefits between any two sources is constant. Put more simply, this benefit function implies that emissions abatement at any source is a perfect substitute for emissions abatement at any other source.

Substituting the appropriate derivatives of (36) into the definitions of b_i (15) and ϕ_{ij} (16) allows one to show that for this benefit function

$$(37) \qquad B_{ii} = B_{ij}b_i / b_j = B_{jj}b_i^2 / b_j^2$$

Substituting (37) into (30) and simplifying, using the permit-market clearing condition (5), the equation for the optimal permit trading ratios (24), and the independence of costs between sources (18) give a simplified expression for the comparative advantage of tradable permits relative to emissions quotas

(38) $$\Delta^{PQ} \approx E \sum_i - \beta_i(\ )\hat{q}_i + \frac{1}{2}\beta_{ii}\hat{q}_i^2$$

Note that this expression is just equal to the difference in expected costs between a tradable permit system and an emissions quota system. Because in this case abatement at any source is a perfect substitute for abatement at any other source, permit trades do not affect the total benefits from abatement.

Substituting the expression for the amount of abatement under the optimal permit system (28) into (38) and simplifying give

(39) $$\Delta^{PQ} \approx \sum_i \frac{\sigma_i^2}{2\beta_{ii}^2}\left[-b_i^2 + \beta_{ii}\right] = \sum_i \frac{\sigma_i^2}{2\beta_{ii}^2}\left[-b_i^2 + \sum_j b_j^2\right] = \sum_i \frac{\sigma_i^2}{2\beta_{ii}^2}\sum_{j\neq i} b_j^2$$

Since $\sigma > 0$, this shows that $\Delta^{PQ} > 0$, which implies that when benefits take this form, tradable permits always dominate emissions quotas. The intuition behind this result is simple. As noted above, when benefits take this form, only the expected cost differs between the two instruments; the expected benefits are the same. Tradable permits have a lower expected cost, because they allow firms to shift abatement to the lowest cost source, whereas emissions quotas do not allow such flexibility.

Substituting (39) into (34) and simplifying give an expression for the comparative advantage of tradable permits relative to emissions taxes for this case

(40) $$\Delta^{PT} \approx \sum_i \frac{\sigma_i^2}{2\beta_{ii}^2}\left(-\gamma - \mu\right)$$

where γ is the slope of the marginal benefit curve with units of abatement normalized to equal the amount of emissions allowed by one permit. Thus,

(41) $$\gamma = \beta_{ii}/b_i^2$$

Note that (37) implies that the value of the term on the right-hand side of (41) is the same for all *i*.

Since $\gamma < 0$ and $\mu > 0$, the sign of Δ^{PT} is ambiguous. μ, the slope of the market demand function for emissions permits, can also be interpreted as the slope of the market-wide marginal cost curve, with units of abatement normalized to equal the amount of emissions allowed by one permit. This market-wide marginal cost curve will be flatter than any single source's marginal cost curve (since it equals the horizontal sum of all sources' marginal cost curves). Expression (40) shows that

12

taxes dominate permits if the market-wide marginal cost curve is steeper than the marginal benefit curve. If the marginal benefit curve is steeper, then permits dominate taxes.

This can be seen as an analogue of Weitzman's (1974) result comparing price and quantity instruments; quantity regulation dominates if the marginal benefit curve is steeper than the marginal cost curve, while price regulation dominates if the marginal cost curve is steeper. The difference is that for multiple sources regulated through a system of tradable permits, the appropriate marginal cost curve is the market-wide marginal cost curve, whereas when using a quantity instrument to regulate a single source, it is that source's marginal cost curve.

Thus, when the benefit function takes the form assumed here, tradable permits always dominate emissions quotas. When comparing tradable permits to emissions taxes, either instrument may dominate, depending on the relative steepness of the market-wide marginal cost and marginal benefit curves.

ii. When Abatement Benefits Are Independent Across Pollution Sources

A second illustrative special case occurs when the marginal benefit of abatement from one source is independent of the amount of abatement at any other source. For this to be the case, the benefit function must be additively separable, taking the form

$$(42) \qquad B(q) = \sum_i B_i(q_i)$$

Benefits would take this form if pollution is very localized–that is, if there is no mixing of emissions from different sources. Substituting the second derivatives of (42) into the definition of γ_{ij} (16) gives

$$(43) \qquad \gamma_{ij} = 0 \quad i \neq j$$

Substituting (43) into the expression for the comparative advantage of tradable permits relative to emissions quotas (33) and simplifying, using the definition of σ (27) yield

$$(44) \qquad \Delta^{PQ} \approx \sum_i \frac{\sigma_i^2}{2\gamma_{ii}^2}\left(\gamma_{ii} + \beta_{ii}\right)\left(1 - \frac{b_i^2}{\gamma_{ii}}\right) + \frac{\beta_{ii}}{2\gamma_{ii}^2} b_i^2 \sum_{j}^{2}\left(\frac{b_j^2 \sigma_j^2}{\gamma_{jj}^2} - \frac{b_j^2 \sigma_i^2}{\gamma_{ii}\gamma_{jj}}\right)$$

13

Note that the first term in the summation is equal to Δ^{TQ}, the comparative advantage of taxes relative to quotas, times $1 - \dfrac{b_i^2}{\phi_{ii}}$. Using the definition of ϕ (27),

$$(45) \qquad 1 - \frac{b_i^2}{\phi_{ii}} = 1 - \frac{b_i^2}{\phi_{ii}} \bigg/ \sum_j \frac{b_j^2}{\phi_{jj}} = \sum_{j \ne i} \frac{b_j^2}{\phi_{jj}} \bigg/ \sum_j \frac{b_j^2}{\phi_{jj}} \qquad 0 \le 1 - \frac{b_i^2}{\phi_{ii}} \le 1$$

Therefore, the first term in (44) will have the same sign as Δ^{TQ}, but will have a smaller magnitude. This reflects the fact that permits offer firms more flexibility than emissions quotas, because the amount of abatement is not fixed at each source, but less flexibility than emissions taxes, because the total amount of abatement is fixed. Given this form for the benefit function–unlike the form considered in the previous section–the added flexibility relative to a system of quotas is not necessarily beneficial. Permit trading reduces the expected cost, but also reduces the expected benefit, because the marginal benefit of abatement falls at the sources that do more abatement, while it rises at the sources that do less abatement.

The second term reflects the fact that the variation in abatement is distributed in a fundamentally different fashion under tradable permits than under emissions taxes or quotas. The form of the benefit function implies that the optimal amount of abatement at a given source depends only on the variation in abatement cost at that source. Under taxes, cost variation at one source will only cause the amount of abatement to vary at that source; no other source is affected. Under quotas, the amount of abatement at each source is fixed. Thus, under either of these two instruments, variation in cost at a given source will cause abatement to deviate from the optimal amount only at that source. In contrast, under tradable permits, cost variation at one source will affect the price of permits. Therefore, the deviation from the optimal amount of abatement resulting from cost variation at one source isn't concentrated at that source, but is spread over all sources.

The second term measures the expected difference in benefits and costs that results from this difference. Thus, it depends on the variance in costs at each source and on the slopes of the marginal benefit and marginal cost curves at each source, which determine how much deadweight loss results when abatement deviates from the optimal amount at that source.

This term depends on σ_i^2/ϕ_{ii}, the variance in abatement for a given permit price, and on ψ_{ii}/ϕ_{ii}, the ratio of the slope of the marginal benefit curve to the slope of the marginal cost curve,

which determines the comparative advantage between price and quantity instruments at that source. If the sources are symmetric in either respect–if either σ_i^2/γ_{ii} or β_{ii}/γ_{ii} is constant for all i,–then the second term in (44) will equal zero. The sign of the first term depends on the same factor that determines the sign of Δ^{TQ}–whether the magnitude of β_{ii} is larger or smaller than that of γ_{ii}. Thus, if quotas are favored over taxes at each source, then quotas will be favored over tradable permits.

When the sources are not symmetric in either respect, the sign of the second term in (44) is ambiguous. If σ_i^2/γ_{ii} is larger than average at the same sources where β_{ii}/γ_{ii} is larger than average, then this term will be positive. It will be negative if σ_i^2/γ_{ii} is larger than average at the same sources where β_{ii}/γ_{ii} is smaller than average. When this term is positive, it is possible for tradable permits to dominate emissions quotas even when quotas dominate taxes. For this to occur, however, β_{ii} and γ_{ii} must be of similar magnitude, because otherwise the first term in (44) will dominate the second term.

We can also calculate the comparative advantage of tradable permits over taxes for this form of the benefit function, by substituting (44) into (34) to get

$$(46) \qquad \Delta^{PT} \approx \sum_i \frac{\sigma_i^2}{2\gamma_{ii}^2}\left(\beta_{ii}+\gamma_{ii}\right) - \frac{b_i^2}{\gamma_{ii}} + \frac{\beta_{ii}}{2\gamma_{ii}^2}b_i^2 \quad 2\sum_j \frac{b_j^2\sigma_j^2}{\gamma_{jj}^2} - \frac{b_j^2\sigma_i^2}{\gamma_{ii}\gamma_{jj}}$$

The second term is the same as in (44), so it will be zero under the same symmetry conditions. As in (44), the sign of the first term depends on β_{ii} and γ_{ii}. Therefore, if taxes are favored over quotas at each source, then taxes will be favored over tradable permits.[11]

Thus, when the benefit of abatement at a given source is independent of the amount of abatement at all other sources, as long as the sources are sufficiently symmetric, tradable permits will be dominated by either taxes or quotas. In other words, in this case, permits will never be the best of the three instruments.

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[11] If the marginal benefit curve is steeper than the marginal cost curve for some sources, but the marginal cost curve is steeper for other sources, then it is possible for tradable permits to dominate both taxes and quotas even when the second term in (44) and (46) is zero. However, in such a case, tradable permits would be dominated by a mixed system–one that uses taxes to regulate sources where the marginal cost curve is steeper, and quotas to regulate the sources where the marginal benefit curve is steeper.

III. Intertemporal Trading: Permit Banking and Borrowing

Thus far, the model has been presented solely as a model of intratemporal permit trading–trading among different sources within a given time period. However, the same model can be used to examine permit banking and borrowing, which are, in effect, permit trades between different time periods.[12] This section presents a simple model of pollution regulation in a dynamic setting–first for a flow pollutant, and then for a stock pollutant–and then uses the tools developed in the previous section to examine the efficiency of bankable permits relative to taxes and fixed quotas.

A. Regulation of a Flow Pollutant

First, we consider regulation of a flow pollutant–that is, a pollutant that causes damage only in the period in which it is emitted. The discounted benefits and costs of abatement are given by

$$(47) \qquad B = \sum_{i=0} \delta^i B(q_i)$$

$$(48) \qquad C = \sum_{i=0} \delta^i C(q_i, \delta_i)$$

where δ is the discount factor, which is assumed to be the same for firms and for the regulator. Note that this benefit function is additively separable across abatement in different time periods, and thus corresponds to the form assumed in section II.D.ii. Therefore, the conclusions of that section will apply here.

Taking a derivative of (47) and using the definition of b (15) and the expression for the optimal trading ratios (24), we can calculate the rate at which emissions reductions in period i should convert into allowable increases in emissions in period j, through either banking or borrowing

$$(49) \qquad \frac{r_i}{r_j} = \frac{b_i}{b_j} = \delta^{i-j}$$

This implies that banked or borrowed permits should "accrue interest" at the discount rate. This is the same conclusion reached by Kling and Rubin (1997) in their analysis of permit banking for a

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[12] Because the model assumed that firms have no uncertainty about costs in setting abatement at each source, translating this model into a dynamic context requires the assumption that all cost uncertainty is revealed before firms choose their levels of abatement for the first period. In practice, this assumption generally will not hold, but this should not substantially affect the results.

flow pollutant without uncertainty. Substituting the second derivatives of (47) and (48) into the

definitions of γ (14) and η (16) yields

(50) $\qquad \gamma_{ii} = {}^iC''(\bar{q}_i)$

(51) $\qquad \eta_{ij} = {}^iB''(\bar{q}_i)$ $\quad i = j$ $\qquad \eta_{ij} = 0$ $\quad i \neq j$

Dividing (51) by (50) yields

(52) $\qquad \dfrac{\eta_{ii}}{\gamma_{ii}} = \dfrac{{}^iB''(\bar{q}_i)}{{}^iC''(\bar{q}_i)} = \dfrac{B''(\bar{q}_i)}{C''(\bar{q}_i)}$

Because the stationarity of the cost and benefit functions in each period implies that $\bar{q}$ will be

constant over time, the ratio of η_{ii} to γ_{ii} will also remain constant, thus satisfying one of the

symmetry conditions from section II.D.ii. Thus, based on the results of that section, bankable permits

will be dominated either by taxes or quotas. If $\gamma_{ii} + \eta_{ii} > 0$ – if the marginal cost curve for abatement

in each period is steeper than the marginal benefit curve–then taxes will dominate bankable permits.

If the marginal benefit curve is steeper, then quotas will dominate bankable permits.

Thus, as a general rule, permit banking should not be allowed for flow pollutants; if it is better

to use a quantity instrument than a price instrument, then non-tradable quotas will dominate tradable

permits. In practice, nearly all emissions permit programs allow firms to bank permits. For example,

the 1990 Clear Air Act Amendments, California's Low-Emission Vehicle Program, the CAFE vehicle

fuel-economy standards, and the leaded gasoline phaseout program all allowed permit banking in

some form.

There are some exceptions. If the ratio of η_{ii} to γ_{ii} and the amount of cost uncertainty vary

significantly across periods, then it is possible for bankable permits to dominate taxes and quotas,

though the conditions under which this will occur are quite restrictive, and thus it seems unlikely that

they will occur in practice. A more promising argument for the use of bankable permits to regulate a

flow pollutant would be if $\gamma_{ii} + \eta_{ii} > 0$ – and thus emissions taxes dominate the other two

B. Regulation of a Stock Pollutant

Consider instead the case of regulation of a stock pollutant–one for which pollution damages in a given period depend on the amount of emissions in all previous periods. In this case, the benefit function will take the form.

$$(53) \qquad B = \sum_{i=0}^{} {}^i\hat{B}\left(\sum_{j=0}^{i} s^{i-j} q_j\right)$$

where s is the stock decay factor. The term in parentheses is the stock of pollution at time i. Unlike in the case of the flow pollutant, the marginal benefit from abatement in one period depends on the amount of abatement in other periods, so this benefit function does not fit the form analyzed in section II.D.ii. Nor does it fit the form analyzed in section II.D.i, in which abatement in any period is a perfect substitute for abatement in any other period, though it is close. To see this, consider the expression for b_i in this case (taking a derivative of (53) and substituting into the definition of b_i (15))

$$(54) \qquad b_i = \sum_{k=i}^{} {}^k\hat{s}^{k-i}\hat{B} \qquad \frac{b_i}{b_j} = s^{j-i} + \frac{\sum_{k=\min(i,j)}^{\max(i,j)} {}^k s^{k-i}\hat{B}}{\sum_{k=i}^{} {}^k s^{k-i}\hat{B}}$$

The ratio of the marginal benefit from abatement in period i to that in period j is a constant plus the discounted value of avoided damages between the two periods divided by the marginal benefit in period i.[14] If this second term were zero, then abatement would be perfectly substitutable

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[13] Adjustment costs are sometimes raised as another argument for allowing banking. A full analysis of the impact of adjustment costs is beyond the scope of this model–if adjustment costs are significant, the marginal cost of abatement in one period depends on abatement in other periods, which would make the analysis much more complicated–but the intuition is fairly simple. When adjustment costs are significant, more abatement in one period lowers the marginal cost of abatement in later periods, which implies that the optimal amount of abatement in those periods will be higher. However, with permit banking, more abatement in one period implies just the opposite; less abatement is required in later periods. Thus, permit banking is even less efficient when adjustment costs are important.

[14] Note that the ratio in (54) is also the optimal rate at which emissions reductions in period i can be banked and used to allow increased emissions in period j. This implies that banked permits should "earn interest" at a rate equal

between the two periods. This is the case in the limit as both the stock decay factor and the discount factor go to one. In that case the damages that occur after period j–for which abatement is perfectly substitutable between the two periods–swamp the effects that occur in the interval between period i and period j.

Thus, the results from section II.D.i will apply in the limit as the stock decay factor and discount factor go to one. While neither factor will actually equal one in practice, as long as both factors are close to one, abatement in one period will be a close substitute for abatement in other periods. In that case, bankable permits will tend to dominate emissions quotas. This suggests that the recent Kyoto protocol targets for greenhouse gas emissions are unnecessarily inefficient, because they do not incorporate any provisions for banking or borrowing.

Similarly, the choice between bankable permits and taxes would depend on the relative slopes of the marginal benefit and cost curves, where the appropriate marginal cost curve is the cost curve for emissions reductions in all periods. This result is also potentially quite important for policy decisions. Newell and Pizer (1998) found that taxes are generally superior to emissions quotas for the regulation of long-lived stock externalities, because the marginal benefit curve is relatively flat compared to the marginal cost curve for a single period. However, Newell and Pizer's study did not consider bankable permits. The marginal cost curve for abatement over all periods will be much flatter than the curve for any single period, since it is the horizontal sum (weighted by discounted marginal damages) of the cost curves across all periods. As a result, while taxes will generally be superior to emissions quotas, there are a significant range of cases in which bankable permits will dominate taxes. Thus, the argument for using taxes to regulate long-lived stock pollutants is not so clear-cut once bankable permits are considered.

IV. Conclusions

This paper develops a framework to evaluate the relative efficiency of three different instruments–taxes, quotas, and tradable or bankable permits–for the control of pollution that is

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to the ratio of current marginal damages to the discounted value of future marginal damages, minus the stock decay rate. This is the same conclusion reached by Leiby and Rubin's (2000) study of permit banking in regulation of a stock pollutant without uncertainty.

produced by multiple sources spread over different locations or different time periods. It then applies that framework in several illustrative cases.

This paper shows that when pollution abatement at any location is a perfect substitute for abatement at any other location–as is the case for a globally mixed pollutant, for example–tradable permits will always be more efficient than fixed emissions quotas. The choice between tradable permits and emissions taxes in this case depends on the relative slopes of the marginal cost and marginal benefit curves. If the marginal cost curve is steeper, then taxes dominate, while if the marginal benefit curve is steeper, tradable permits dominate. This result is similar to that found by Weitzman (1974) in comparing price and quantity instruments. The difference in this case is that the appropriate marginal cost curve is the market-wide cost curve. This is equal to the horizontal sum of the cost curves of each individual source, and is therefore flatter than any individual source's cost curve.

In the alternative case in which the marginal benefit of abatement at a given location is independent of the amount of abatement at other locations–as would be the case when pollution damages are highly localized–tradable permits are typically dominated by either quotas or taxes. Only when sources are sufficiently asymmetric, both in the amount of uncertainty about costs and in the slopes of the marginal benefit and marginal cost curves, can tradable permits be the most efficient instrument, and even then only under fairly restrictive conditions on other parameters.

Analogous results apply when banking and borrowing of permits is allowed in a dynamic setting, because such transactions are essentially permit trades that occur across time rather than across locations. The case of a flow pollutant corresponds to the case of entirely localized pollution, because marginal pollution damage in a given period depends only on emissions in that period. In this case, bankable permits are typically dominated by either quotas or taxes; bankable permits are the most efficient instrument only under quite restrictive conditions.

For a stock pollutant, especially one with a low decay rate, abatement in one period is a close substitute for abatement in other periods. Thus, bankable permits will generally dominate emissions quotas, though this will not always be the case; quotas will dominate if the stock decay rate and discount rate are sufficiently high, and the marginal benefit curve is substantially steeper than the marginal cost curve. The choice between bankable permits and taxes will depend on the relative

slopes of the intertemporal marginal cost curve (which will be substantially flatter than the cost curve in a single period) and the marginal benefit curve.

These results could have tremendous importance for environmental policy. They strongly suggest that many current and proposed environmental regulations are not optimal. Emissions permit programs for flow pollutants typically allow banking (for example, the lead phase-out and sulfur dioxide permit programs), while the Kyoto agreement to reduce carbon dioxide emissions–a stock pollutant–does not allow for such intertemporal flexibility. The results also suggest that tradable permits should not be used for highly localized pollutants.

A few caveats are in order. Several simplifying assumptions have been made. Most notably, this analysis assumes that the marginal cost of abatement at each source does not depend on the amount of abatement at any other source, and that marginal abatement cost shocks are uncorrelated across different sources. The first assumption may well be violated, especially in an intertemporal context if abatement capital or adjustment costs play an important role. In each of these cases, increased abatement in one period would decrease the marginal cost of abatement in other periods, which would increase the optimal amount of abatement in those periods. However, under tradable permits, the amount of required abatement in those periods would decrease. Thus, in these cases, bankable permits would tend to be less efficient than this model indicates.

The second assumption could also be violated. This is particularly likely in an intratemporal context, for example as a result fluctuations in the price of an emissions-reducing input; if the price of low-sulfur coal rises, sulfur dioxide abatement costs will tend to rise at all coal-burning pollution sources. Such correlations would tend to make tradable permits behave more like emissions quotas. If cost shocks are perfectly correlated, then they will cause the permit price to change, but will have no effect on the quantity of abatement at each source; thus, the efficiency of tradable permits will be the same as that of emissions quotas.

The model also assumes that firms have no uncertainty about costs in making their abatement decisions. While this may be a reasonable assumption when looking at permit trading in a static context, it is somewhat more troubling for modeling permit banking in a dynamic context, where firms may well be uncertain about costs in later periods when making decisions in earlier periods. This should not dramatically alter the results, but it warrants further study.

21

These results suggest a number of possible directions for future research. The framework developed here could be used to consider some variations on unlimited permit trading. For example, some programs allow trading only within a local area, rather than across the entire universe of pollution sources. The question of how large these trading areas should be is quite interesting.

Similarly, Roberts and Spence (1976) showed that hybrid instruments–instruments that combine elements of both taxes and quotas, such as emissions permits with a price cap–will always be more efficient than a pure price or pure quantity instrument. A similar result should hold for hybrids between tradable and non-tradable (or bankable and non-bankable) permits. And unlike price/quantity hybrid instruments, tradable/non-tradable hybrids are common. Most emissions permit programs allow permit banking, but not permit borrowing.[15] These programs behave like bankable permit systems when firms choose to bank permits, but behave like fixed emissions quotas when firms would like to borrow permits. Further research could determine whether such hybrid instruments are more efficient, as was the case for the price/quantity hybrids analyzed by Roberts and Spence.

Finally, empirical applications of this framework would be very useful for policy. Given the increasingly rich data on environmental regulation that is becoming available, it should not be too difficult to estimate the parameters of interest for a particular case.

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[15] Similarly, the RECLAIM program in the Los Angeles area allows permits to be traded from emissions sources near the coast to sources located inland, but not vice-versa.

References

Cronshaw, M., and J. Kruse, 1996. "Regulated Firms in Permit Markets with Banking," *Journal of Regulatory Economics*, 9:179-189

Kaplow, Louis and Steven Shavell, 1997. "On the Superiority of Corrective Taxes to Quantity Regulation," NBER Working Paper #6251

Kling, Catherine and Jonathan Rubin, 1997, "Bankable Permits for the Control of Environmental Pollution," *Journal of Public Economics*, 64:101-115

Leiby, Paul and Jonathan Rubin, 2000, "Bankable Permits for the Control of Stock Pollutants: The Greenhouse Gas Case." working paper, Oak Ridge National Laboratory and the University of Maine

McGartland, Albert and Wallace Oates, 1985, "Marketable Permits for the Prevention of Environmental Deterioration," *Journal of Environmental Economics and Management* 12:207-228

Montgomery, W. David, 1972, "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory* 5:395-418

Newell, Richard and William Pizer, 1998, "Regulating Stock Externalities Under Uncertainty," working paper, Resources For the Future

Roberts, Marc and Michael Spence, 1976, "Effluent Charges and Licenses Under Uncertainty," *Journal of Public Economics*5:193-208.

Rubin, Jonathan, 1996. "A Model of Intertemporal Emission Trading, Banking, and Borrowing," *Journal of Environmental Economics and Management*, 31:269-286

Stavins, Robert, 1996, "Correlated Uncertainty and Policy Instrument Choice," *Journal of Environmental Economics and Management*, January 1996

Weitzman, Martin, 1974, "Prices vs. Quantities," *Review of Economic Studies* 41:477-491