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Incentives for Pollution Control

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Incentives for Pollution Control

by

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ABSTRACT

The paper reports on some central results of the Incentives for Pollution Control project. I outline the analyses and results of two theoretical investigations into the incentives for the adoption of cleaner technologies. The first examines the incentive effects of pollution taxes and tradeable pollution permits. The second examines the optimal design of a permit trading system in the presence of uncertainty about environmental impacts and the evolution of information about those impacts over time. The central message of this research project is that the pricing of pollution, through mechanisms like pollution taxes and tradeable pollution permits, is likely to be the best approach to the regulation of the forest products processing industry. Pricing provides short run incentives to reduce pollution based on currently employed technology, and at the same time creates long run incentives for the adoption of new, cleaner technologies. If these pricing policies are designed well - according to the principles delineated in the results of this research project - then they can induce an optimal balance between the benefits of reduced environmental impact and the costs of switching to cleaner technologies. Achieving that balance is crucial to sustaining the boreal forests and at the same time sustaining the economic benefits derived therefrom.

INTRODUCTION

This project investigates the impact of a variety of environmental regulatory mechanisms on incentives for the adoption of less polluting technologies. The analysis is theoretical in nature but has wide application to a variety of practical settings, including the forest products sector. The implementation of cleaner technologies is likely to be one of the most cost-effective strategies for reducing the environmental impact of the forest products sector while maintaining its long term economic viability. Thus, the question of how best to create the correct incentives for new technology adoption is central to sustainable forest management.

This report presents a summary of results on two key components of the research project. The first component focuses on the relative impact with respect to incentives of two basic regulatory mechanisms: pollution taxes and tradeable pollution permits. Pollution taxes are levied on the volume of polluting effluent (for example, from a pulp mill) such that the polluting firm pays for the quantity of effluent discharged. Thus, the larger the quantity of effluent discharged (adjusted for concentration and toxicity), the more the firm pays. This creates a financial incentive for the firm to reduce its discharges. In the short run that reduction may be relatively small, since it can only be achieved by reducing production. However, in the long run, the firm will pursue alternative technologies that allow production with less discharge. The financial reward in the form of lower tax payments, creates the incentive for the pursuit of those technologies.

An alternative regulatory mechanism is tradeable pollution permits. A permit system specifies a target aggregate volume of discharge from all sources into a regulated water body (or airshed in the case of airborne emissions). Unit permits totaling that aggregate target are then issued to the polluting firms, either by auction or some alternative scheme (such as grandfathering). A firm must hold a permit for each unit of effluent discharged. The critical element of the permit scheme is that permits are tradeable amongst the polluting firms. That is, one firm can buy permits from another firm such that the buying firm's higher discharges are offset by the selling firm's lower discharges; the aggregate target is not compromised. The tradeability of permits creates a market price for those permits, with two important consequences. First, the distribution of aggregate discharges across polluting firms conforms to that which ensures that the aggregate target is met at lowest aggregate cost. Second, the pricing of permits through the market creates a financial incentive for firms to pursue less polluting technologies, in much the same way as a pollution tax. The first component of the research project examines the relative merits of tradeable pollution permits and pollution taxes in creating incentives for new technology adoption.

The second component of the project focuses specifically on tradeable pollution permits in the context of a regulatory setting where the environmental impact of the regulated pollutant is uncertain. The particular issue of interest is the manner in which an aggregate pollution target should be adjusted in response to new information about the toxicity of a pollutant, and how that adjusted should be implemented under a tradeable permits system. The approach adopted by the regulator with respect to permit system adjustment is crucial for the incentives created by the permit system for the adoption of cleaner technologies. In particular, those incentives can be undermined entirely if the adjustment is undertaken in a way that introduces significant capital risk associated with holding permits. The research results provide a set of guidelines as to how adjustment can be made in response to new information without degrading the incentives for cleaner technology adoption.

The rest of this report is organized as follows. The next section presents a summary of the analysis and main results. A following section describes the management applications of the results. A brief conclusion closes the body of the report.

SUMMARY OF ANALYSIS

This section presents a summary of the two project components described above. The first component is titled "Environmental Policy and Technological Change: Emission Taxes and Emissions Trading"; this is joint work with Benoit Laplante of the World Bank. The second component is titled "Learning About Environmental Damage: Implications for Emissions

Environmental Policy and Technological Change: Emission Taxes and Emissions Trading

I begin by outlining a simple analytical framework in which our results are derived. I then presents the main results, in two parts: one on pollution (or emission) taxes, the other on pollution (or emission) permits.[1]

Analytical framework

Time is divided into two periods. In period 1 each of *n* firms uses a production technology with associated abatement cost function $c_0(\bar{e}_0 - e)$, where *e* denotes emissions, and

[1] A more complete description of this research can be found in Kennedy and Laplante (2000).

$\bar{e}_0$ is the level of emissions corresponding to no abatement. Thus, $\bar{e}_0 - e$ represents abatement. Abatement may involve a variety of measures, including a reduction in output, a change in inputs or some end-of-pipe remedial action. The abatement cost function measures the least cost mix of abatement measures. Abatement cost has the following important properties: $c_0' > 0$ and $c_0'' > 0$.

A cleaner technology becomes available at the beginning of period 2. It can be adopted by any firm at some fixed installation cost *K*. This technology has an associated abatement cost function $c_1(\bar{e}_1 - e)$ with $c_1' > 0$ and $c_1'' > 0$, where $\bar{e}_1 \leq \bar{e}_0$ and $c_1' < c_0'$ for any $e \leq \bar{e}_0$. Thus, any positive level of abatement can be achieved at lower cost with the new technology.

Polluting firms are assumed to be price-takers on the product market. This means that private and social marginal abatement cost coincide. It is important to note that this assumption can hold even if the number of polluting firms in the regulated region is small since the regulated firms do not necessarily constitute the whole industry. Such is the case, for example, when polluting firms take world prices as given.

Environmental damage *D(E)* in any period is an increasing function of aggregate emissions *E* in that period. That is, attention is restricted to the case of a dissipative pollutant that is uniformly mixed relative to the regulated region. Two cases are considered with respect to the damage function: $D''(E) > 0$ (strictly convex damage) and $D''(E) = 0$ (linear damage).

Pollution taxes

The timing of the game between the firms and the regulator is as follows. In period 1 the tax is set according to the Pigouvian rule for the prevailing technology. The new technology arrives at the beginning of period 2 and the regulator announces a tax rate for that period. Firms then decide whether or not to adopt the cleaner technology, taking as given the simultaneous technology adoption decisions of other firms. The regulator cannot commit to a tax rate that is time inconsistent. That is, the tax rate announced for period 2 must be consistent with the technology choices that the tax induces.

The equilibrium to the game between the firm and the regulator depends importantly on whether damage is linear or strictly convex. In the case of linear damage, the unit tax rate on emissions is set equal to marginal damage: $t^* = d$. Note that this optimal tax rate is independent of which technology is in place because marginal damage is constant. The firm responds to the tax by setting its emissions level to equate its marginal abatement cost with the tax rate:

$c_i'(\bar{e}_i - e_i) = t^*$. Thus, the firm chooses e_0^* if it uses the old technology, and e_1^* if it uses the new technology. That is, the emissions tax implements static efficiency for any given technology.

The private benefit to the firm from adopting the cleaner technology comprises the reduction in tax payments, $t^*(e_0^* - e_1^*)$, plus any reduction in abatement cost. Note that the reduced tax payments correspond exactly to the reduced environmental damage since $t^* = d$. It follows that the private benefit to the firm from adopting the new technology is identical to the social benefit. Thus, the emissions tax also implements efficiency with respect to technology adoption.

The regulatory problem is somewhat more complicated when marginal damage is increasing. For an emissions tax to implement the efficient level of emissions for any given technology *i*, the tax rate must be set equal to marginal damage evaluated at the efficient level of emissions; that is, $t_i^* = D'(e_i^*)$. Thus, the tax rate required depends on which technology is in use. This creates a potential time consistency problem for the regulator. If adoption of the new technology is efficient then the regulator would like to announce a tax rate t_1^* for period 2. Conversely, if adoption of the new technology is not efficient then the regulator would like to announce a tax rate t_0^* for period 2. The problem is that a tax rate of t_0^* may actually induce the firm to adopt the *new* technology, while a tax rate of t_1^* may induce the firm to retain the *old* technology. In both cases the announced tax rate would not be optimal *ex post* and hence could not be committed to *ex ante*.

Under what conditions will this time consistency problem arise? Suppose adoption of the new technology is not efficient; that is, $G \le K$. Then the first-best tax rate for period 2 is t_0^*. Figure 1 illustrates the private benefit to the firm from adoption of the new technology at this fixed tax rate. If the firm retains the old technology then it sets emissions equal to e_0^*. Conversely, if it adopts the new technology then it sets emissions equal to $e_1(t_0^*)$. Let $B(t_0^*)$ denote the private benefit from adoption at t_0^*. Note that $B(t_0^*) > G$. That is, the private benefit from adoption at t_0^* exceeds the social benefit from adoption. This does *not* necessarily create a time consistency problem. In particular, if $B(t_0^*) \le K$ then adoption of the new technology is not privately worthwhile for the firm, and so t_0^* is optimal *ex post*. In this case the announced t_0^* tax rate is credible, and the Pigouvian tax policy implements efficiency with respect to technology adoption.

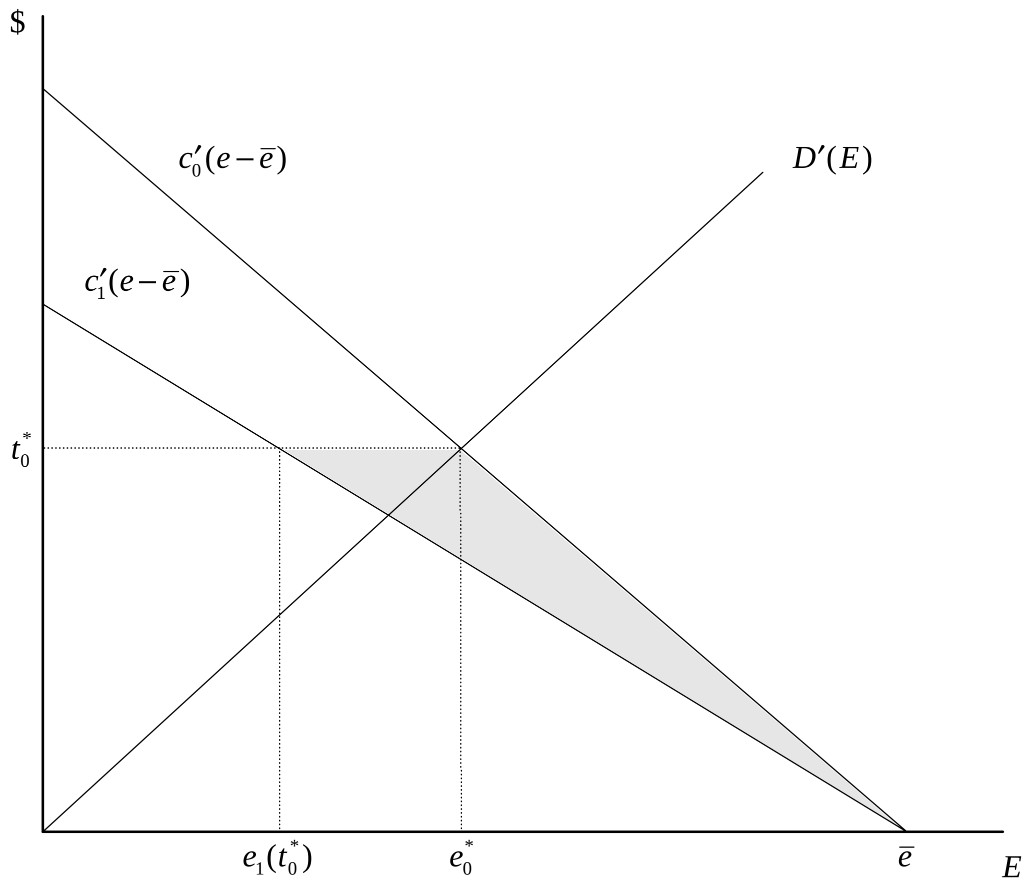

Figure 1: Private benefit from technology adoption.
$(at\ t_0^*)$

However, if $B(t_0^*) > K$ then t_0^* will induce adoption of the new technology, and so t_0^* will not be optimal *ex post*. In this case the regulator cannot commit to the first-best tax rate. The best the regulator can do in this case is to announce that it will set the tax at t_0^* if the firm does not adopt the new technology, and set the tax at t_1^* if the firm does adopt the new technology; no other Pigouvian tax strategy is time consistent. Milliman and Prince (1989) refer to this policy as *tax ratcheting*.

Figure 2 illustrates the private benefit to the firm from adoption of the new technology under the tax ratcheting policy. If the firm retains the old technology then it faces a tax rate of t_0^* and sets emissions at e_0^*. Conversely, if it adopts the new technology it faces a tax rate of t_1^* and sets emissions at e_1^*. Let $B(t_0^*, t_1^*)$ denote the private benefit from adoption in this case. Note that $B(t_0^*, t_1^*) > B(t_0^*)$. It follows that if $B(t_0^*) > K \geq G$ then $B(t_0^*, t_1^*) > K \geq G$. Thus, if efficiency calls for retention of the old technology but t_0^* is not time consistent, then the only time consistent policy is ratcheting, and this policy induces the *inefficient* adoption of the new technology.

There is no corresponding problem if efficiency calls for adoption of the new technology (that is, if $G > K$). In this case the first-best tax rate for period 2 is t_1^*. Figure 3 illustrates the private benefit to the firm from adoption of the new technology at this tax rate. If the firm retains the old technology then it sets emissions equal to $e_0(t_1^*)$. Conversely, if it adopts the new technology then it sets emissions equal to e_1^*. Let $B(t_1^*)$ denote the private benefit from adoption at t_1^*. Note from Figure 3 that $B(t_1^*) < G$. That is, the private benefit from adoption at t_1^* is less than the social benefit. This does not create a time consistency problem if $B(t_1^*) > K$ since in that case the firm will adopt the cleaner technology at t_1^* even though $B(t_1^*) < G$. Conversely, if $B(t_1^*) < K$ then t_1^* is not time consistent and the only time consistent policy is tax ratcheting. However, if $G > K$ then $B(t_0^*, t_1^*) > K$ since $B(t_0^*, t_1^*) > G$. Thus, if efficiency calls for adoption of the new technology then ratcheting will always implement that outcome.

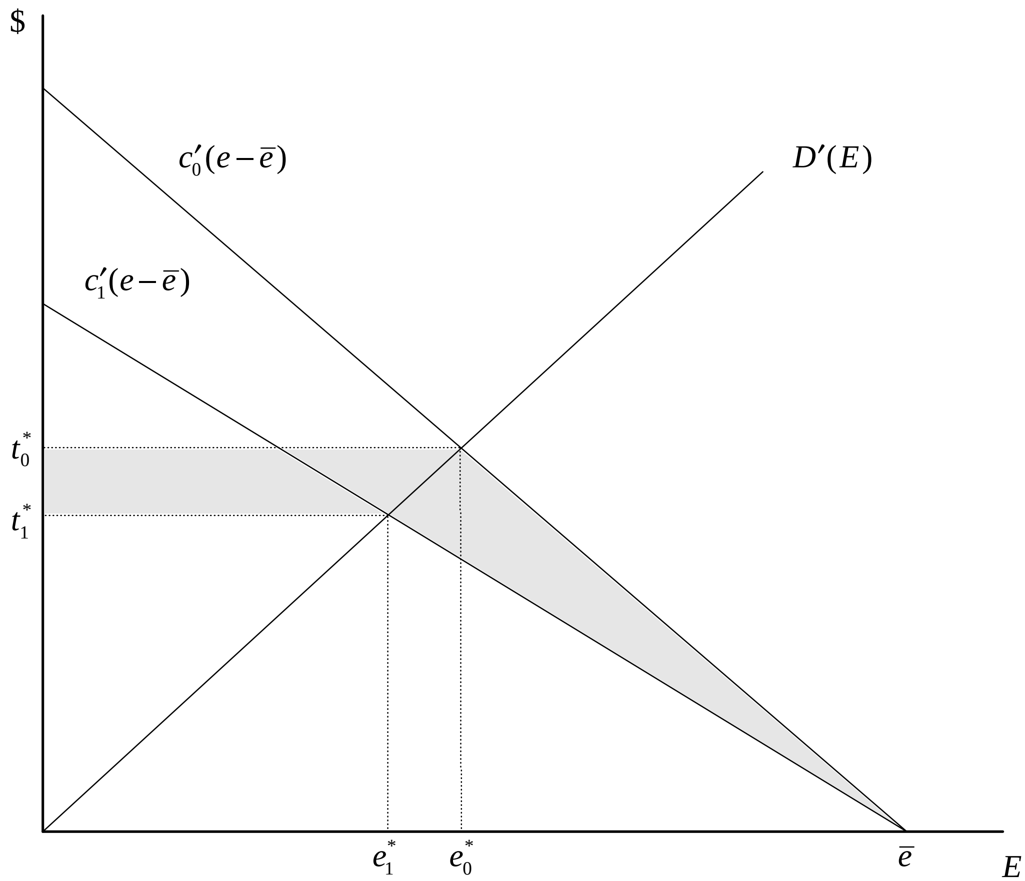

Figure 2: Private benefit from technology adoption under ratcheting.

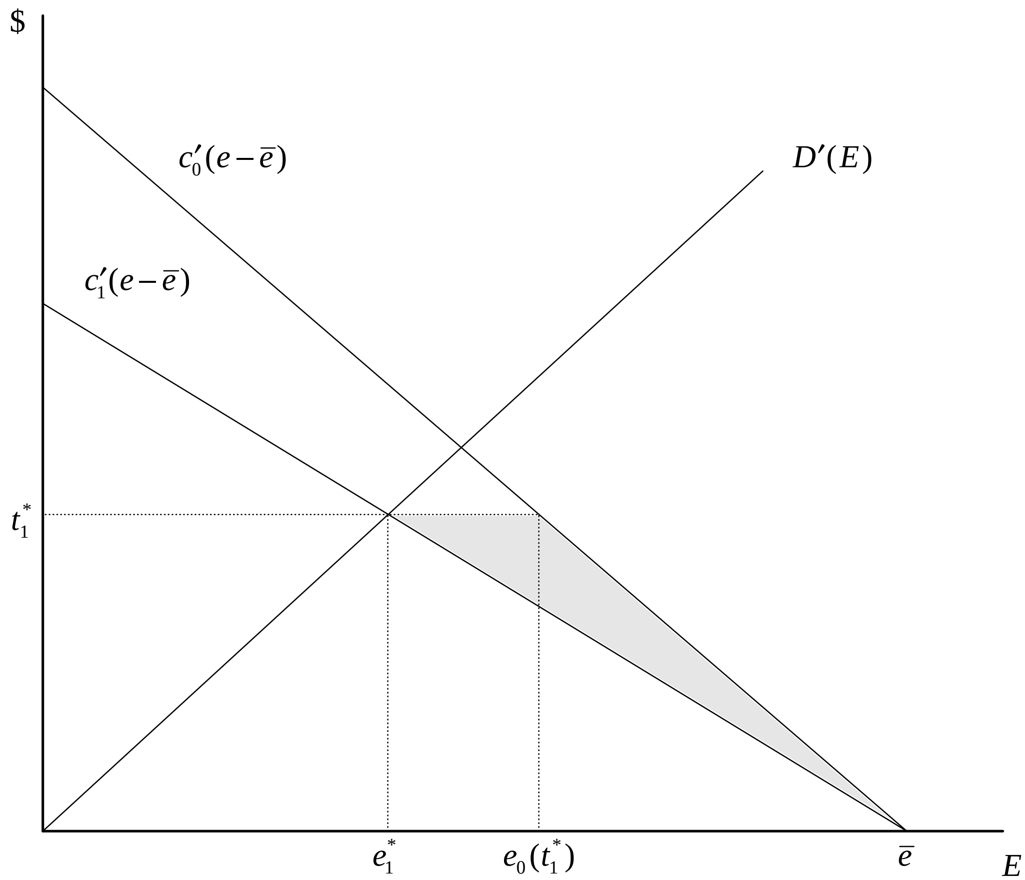

Figure 3: Private benefit from technology adoption.
$(at\ t_1^*)$

These results indicate that the emissions tax cannot induce too little technological change but it can induce too much technological change. This problem with the emissions tax stems from the fact that it does not discriminate across units of emissions according to the damage they cause. The tax rate is set equal to the damage caused by the *marginal* unit of emissions and this tax rate is applied to every unit of emissions. This means that when marginal damage is increasing the total tax payment exceeds the total damage done. In assessing the private benefit to adopting a cleaner technology, the firm thinks in terms of reduced tax payments but what matters from a social perspective is reduced damage. Since the reduction in tax payments under ratcheting exceeds the reduction in damage, the firm's incentive is distorted in favour of cleaner technology adoption. This generates the wrong technology choice if efficiency calls for retention of the old technology.

Pollution permits

We examine a tradeable permit program that operates in the following way. At the beginning of period 1 the regulator issues an aggregate number of permits corresponding to the efficient level of emissions based on the existing technology (used by all firms in period 1). It is not important for the problem at hand whether permits are issued by auction or through some sort of grandfathering scheme provided that the initial distribution does not create asymmetric market power. Each permit allows one unit of emissions during period 1. We assume that no banking is allowed (which means that permits unused in period 1 cannot be carried forward to period 2). The new technology arrives at the beginning of period 2 and the regulator then issues permits for use in period 2. The regulator may or may not then have to re-adjust that supply of permits in response to the technology adoption that actually occurs in equilibrium, depending on whether or not the first-best permit supply is time consistent.

Recall that the first-best tax rate under an emissions tax is the tax rate that induces efficiency with respect to technology adoption and at the same time generates the efficient level of aggregate emissions given the technologies in place. If this tax rate is not time consistent then the regulator must use tax ratcheting. Similarly, the first-best supply of permits (and associated equilibrium permit price) is that which induces efficient technology adoption choices and at the same time corresponds to the efficient aggregate level of emissions, given those technology choices. If this first-best permit supply is not time consistent then the regulator must use a responsive policy, akin to tax ratcheting, whereby the supply of permits is set at the beginning of period 2 and then adjusted *ex post* in response to equilibrium technology choices.

As in the case of an emissions tax, the time consistency of the first-best solution depends on the nature of the damage function. We begin with the case of linear damage. Recall that when damage is linear the regulator does not need to respond to technological change if an emissions tax is used. The tax rate is simply set equal to marginal damage and no adjustment is required. Moreover, this tax rate creates the correct incentives for technological change to occur. Thus, the regulator does not need to respond to the advent of a cleaner technology. In contrast, the advent of a new technology requires a reassessment of the permit supply under an emissions trading program even when damage is linear. In particular, the aggregate supply of permits that is efficient for an existing technology will generally *not* be efficient if a new technology is adopted; the first-best permit supply depends on the technologies in use. Recall from section 3 that when damage is linear, efficiency requires either adoption of the new technology by all firms or retention of the old technology by all firms, depending on the magnitude of the adoption cost. If efficiency calls for universal adoption then the first-best aggregate permit supply is $E_1^* = ne_1^*$ such that $c_1'(\bar{e}_1 - e_1^*) = d$. In contrast, if efficiency calls for universal retention of the old technology then the first-best permit supply is $E_0^* = ne_0^* > E_1^*$ such that $c_0'(\bar{e}_0 - e_0^*) = d$.

Consider first the case where efficiency calls for universal adoption. If the regulator issues the corresponding first-best number of permits then adoption by all firms is the equilibrium response and the permit supply is efficient *ex post*. The key to this result is the fact that the *ex post* equilibrium price of permits is equal to marginal damage; thus, the private benefit from adoption to any individual firm is, in equilibrium, exactly equal to the social benefit.

Similarly, if efficiency calls for retention of the old technology and the permit supply is left unchanged from period 1, then the *ex post* price of permits in an equilibrium with no adoption is equal to marginal damage, and so the private benefit to adoption in that equilibrium is equal to the social benefit. Thus, leaving the supply of permits unchanged between periods is time consistent and induces efficiency.

It is important to emphasize that leaving the supply of permits unchanged in response to the advent of a new technology ensures efficiency with respect to the adoption of that technology only if efficiency calls for no adoption. If the regulator does not adjust the supply of permits *ex ante* then the permit price in a candidate equilibrium in which all firms adopt the new technology would be lower than marginal damage and so the private benefit to adoption in that candidate equilibrium would be less than the social benefit. The private benefit to adoption in the candidate equilibrium could therefore be less than the cost of adoption, in which case adoption by all firms could not in fact be an equilibrium even though adoption by all firms is efficient. Thus, ensuring efficiency when efficiency calls for the adoption of the new technology generally requires an adjustment to the supply of permits in response to the advent of that new technology even when damage is linear.

We now consider the case of strictly convex damage. Recall that when damage is strictly convex the regulator faces a time consistency problem with an emissions tax when there is a relatively small number of firms but that problem vanishes when there are a continuum of firms because each firm is insignificant relative to the aggregate and so perceives an independence between its own choices and the policies implemented by the regulator. The same is true in the case of emissions trading with a continuum of firms: there are no time consistency problems associated with implementation of the first-best policy even when damage is strictly convex.

The policy problem for the regulator in this case is in fact somewhat simpler under emissions trading than under an emissions tax. Recall that strictly convex damage means that efficiency may require strictly partial adoption of the new technology. In that case the regulator must use tax ratcheting since committing to the first-best tax rate *ex ante* cannot induce asymmetric technology choices by *ex ante* symmetric firms, as required for an efficient equilibrium. In contrast, under emissions trading the regulator can set the first-best permit supply at the beginning of period 2, without the need for *ex post* adjustment, and nonetheless induce an asymmetric and time consistent equilibrium.

The key to this result is the flexibility of the permit price to respond to technology adoption choices in equilibrium. The equilibrium price of permits is decreasing in the number of firms that adopt the new technology since the demand for permits is lower when more firms use the new technology. This equilibrating role of the permit price means that the private benefit to any firm from adopting the new technology is decreasing in the number firms using that technology, and this in turn allows an equilibrium to exist in which some firms adopt but additional potential adopters find it unprofitable to do so. No comparable automatic adjustment to the price of emissions occurs under a fixed tax rate policy; hence the need for explicit tax ratcheting.

The equilibrium induced by the first-best supply adjustment is efficient. Each firm takes the permit price as independent of its own action, and since each firm is insignificant relative to the aggregate, marginal damage is effectively constant with respect to the emissions of each individual firm. Thus, the saving to the firm from having to hold fewer permits at the first-best equilibrium price fully reflects the reduction in damage.

Learning About Environmental Damage: Implications for Emissions Trading

I begin by outlining a simple analytical framework in which the results are derived. I then presents the main results.[2]

Analytical framework

Time is divided into two periods. There are a large number of price-taking polluting firms in each period and environmental damage in each period is an increasing function of the flow of their aggregate emissions. Marginal damage is constant and denoted d. The true value of d is uncertain in period 1 and has expected value m. At the beginning of period 2 it becomes known that either $d = d_H$ or $d = d_L < d_H$, where the "H" subscript denotes high damage and the L" subscript denotes low damage. Prior beliefs about d (common to all agents) are represented by $\{p_L, p_H\}$.

At the beginning of period 1 firms must choose between retaining their existing technology and adopting a new cleaner technology. The existing technology has an associated abatement cost function $c_0(\bar{e}_0 - e)$, where e denotes emissions and $\bar{e}_0$ is the level of emissions corresponding to no abatement. Thus, $\bar{e}_0 - e$ represents abatement. Abatement cost is increasing and strictly convex in abatement: $c_0' > 0$ and $c_0'' > 0$. The new technology has an associated abatement cost function $c_1(\bar{e}_1 - e)$ with $c_1' > 0$ and $c_1'' > 0$, where $\bar{e}_1 \le \bar{e}_0$ and $c_1' < c_0'$ for any $e \le \bar{e}_0$. Thus, any positive level of abatement can be achieved at lower cost with the new technology. Adopting the new technology involves a fixed sunk cost *K*.

Results

Efficiency could be implemented by a variety of policy instruments in this setting. One possibility is an emissions fee set equal to expected marginal damage in period 1, and revised in period 2 when the true damage state is realized. However, there are a number of reasons why the regulator may prefer an emissions trading program even in this simple setting. Perhaps most importantly, emissions trading allows the regulator more flexibility with respect to the assignment of pollution rights. An emissions fee assigns the entire cost of pollution to the polluting firms, which may not be consistent with promoting the "international competitiveness" of domestic firms and the employment opportunities associated therewith; rightly or wrongly, such goals are of paramount importance to many policy makers. In contrast, emissions trading allows the implicit assignment of pollution rights to polluting firms, either through the free allocation of permits initially, or through an emissions reduction credit program.

The policy problem

The policy problem is to adjust the supply of permits between periods 1 and 2, in response to the new information about damage, so as to maintain static efficiency in each period and at the same time create the right incentives for technology adoption. That is, firms should have a strict incentive to adopt the new technology if $SB > K$ and a strict incentive not to adopt if $SB < K$. I examine this issue by assessing whether or not the social optimum (as defined by static and dynamic efficiency) is a rational expectations equilibrium in the permit market under a general specification of the supply adjustment rule. The first step is to derive the price path for permits at the optimum.

The permit price path at the social optimum

Suppose technology i is socially optimal and all firms use this technology. Then to achieve static efficiency in period 1 the regulator issues ne_{1i}^* permits in that period, where n is the number of firms. Each permit allows the holder to emit one unit of emissions in each period. The permits may be issued free of charge (according to some type of "grandfathering" rule based on historical emission levels) or they may be auctioned; at this point it does not matter which approach is taken.

The aggregate supply of permits must be adjusted in period 2 once the true value of d becomes known. The efficient level of emissions in period 2 is $ne_{2i}^*(H) < ne_{1i}^*$ if $d = d_H$ and $ne_{2i}^*(L) > ne_{1i}^*$ if $d = d_L$. Firms rationally expect the regulator to adjust the supply of permits in this way; no other policy will achieve static efficiency in period 2 and so no other policy is time consistent. Accordingly, the price path of permits is solved by backward induction beginning in period 2.

Each firm sets emissions in period 2 such that

$$c_i'(\bar{e}_i - e) = p_2 \tag{1}$$

where p_2 is the price of permits in that period. That is, the marginal cost of abatement is just equated to the marginal cost of not abating. Since the supply of permits is set to ensure that $c_i'(\bar{e}_i - e) = d$, it follows that in equilibrium $p_2 = d$. Note that this equilibrium price in period 2 is independent of the manner in which the supply of permits is adjusted between periods 1 and 2

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[2] A more complete description of this research can be found in Kennedy (1999).

since the equilibrium price must clear the market after any adjustment has taken place regardless of how that adjustment is made.

Next consider period 1. The equilibrium price of a permit in period 1 must be such that the return from selling a permit is just equal to the expected return from holding it for that period. The return from selling a permit in period 1 is simply equal to its price in that period, p_1. The expected return from holding a permit for the period is the avoided cost of one unit of abatement (because holding a permit allows one unit of emissions) plus the discounted expected value of a permit carried into period 2. Note that the expected value of a permit carried into period 2 is *not* necessarily equal to the selling price of a permit in period 2; the value of a permit carried forward will generally depend on the supply adjustment rule in place. For example, under a proportional adjustment rule, carrying a permit into period 2 may lead to an increase or decrease in permit holdings through supply adjustment, and this effect will be reflected in the expected value of carrying the permit forward.

To clarify this distinction between expected selling price and expected value, let v_j denote the value of a permit carried forward into period 2. Note that v_j is contingent on the realisation of the damage state (that is, $j = L$ or $j = H$) since the effect of any supply adjustment rule will generally depend on which state is realized. Thus, the equilibrium price of a permit in period 1 when all firms are using technology *i* must be

$$p_1 = c_i'(\bar{e}_i - e_{1i}^*) + b \sum_{j=L,H} p_j v_j \tag{2}$$

Since the supply of permits in period 1 is set such that $c_i'(\bar{e}_i - e_{1i}^*) = m$, it follows that

$$p_1 = m + b \sum_{j=L,H} p_j v_j \tag{3}$$

Thus, since v_j depends on the particular supply adjustment rule in place, so too does the equilibrium price of permits in period 1. This has important implications for investment decisions in that period.

<u>Supply adjustment and dynamic efficiency</u>

Consider the investment incentives for an individual firm when faced with the above permit price path. It is important to note that firms are price-takers on the permit market, which means that an individual firm does not expect the price of permits to depend on its own technology adoption decision. Thus, a firm that deviates unilaterally from the social optimum continues to face the permit prices associated with the social optimum. However, the firm's technology choice will affect the number of permits it carries forward from period 1 to period 2, and this in turn determines the magnitude of any capital gain or loss the firm may experience under the supply adjustment policy. Different supply adjustment policies have different implications for expected capital gains or losses, and therefore have different impacts on technology adoption incentives.

I begin by characterizing the incentives associated with a general specification of the adjustment policy. Let $x_i(j)$ denote the number of permits repurchased (possibly via expropriation) from a firm using technology i when $d = d_j$. (A negative value for $x_i(j)$ means that additional permits are sold or given to the firm). Let q_j denote the price at which permits are repurchased (or sold), contingent on the value of d. Finally, let PB denote the discounted expected private benefit to a firm that adopts the new technology:

$$PB = \left[p_1(e_{10} - e_{11}) + c_0(\bar{e}_0 - e_{10}) - c_1(\bar{e}_1 - e_{11}) \right]$$

$$+ b \sum_{j=L,H} p_j \left[p_2[e_{11} - e_{21}(j) - x_1(j)] - p_2[e_{10} - e_{20}(j) - x_0(j)] \right.$$

$$\left. + q_j[x_1(j) - x_0(j)] + c_0(\bar{e}_0 - e_{20}(j)) - c_1(\bar{e}_1 - e_{21}(j)) \right] \qquad (4)$$

The first term (in square brackets) represents the difference between the two technologies in the value of the permit holdings required in period 1, plus the difference between the two technologies in abatement costs in that period. The second term represents the discounted expected private benefit received in period 2. This has three components. The first component represents the difference between the two technologies in the value of net permit sales at the market price in period 2. The net permit sales for a given technology are equal to the difference between permits required for period 2 emissions and permit holdings carried forward from period 1, less any repurchases; that is, $[e_{1i} - e_{2i}(j) - x_i(j)]$. The second component is the difference between the two technologies in the value of repurchases at price q_j; that is, $q_j[x_1(j) - x_0(j)]$. The third component is simply the difference in abatement cost in period 2 between the two technologies.

Expressions (1) and (4), evaluated at the efficient emission levels and the associated permit prices, yield an expression for the wedge between the private and social benefit from adoption at the social optimum:

$$PB^* - SB = b \sum_{j=L,H} p_j \left[(d_j - q_j)[x_0(j) - x_1(j)] + (e_{10}^* - e_{11}^*)(v_j - d_j) \right] \tag{5}$$

This expression has the following interpretation. The $(d_j - q_j)$ term represents the penalty incurred by the firm when a permit valued at d_j in the market is repurchased by the regulator at price q_j (or conversely, the bonus enjoyed by the firm when a new permit is acquired at less than the market price). The $[x_0(j) - x_1(j)]$ term measures the extent to which the number of permits repurchased (or sold) by the regulator depends on the technology choice made by the firm in period 1. This difference would most obviously arise through a supply adjustment rule that discriminates directly across firms according to their technology. Less obviously, but more importantly, discrimination on the basis of technology may arise indirectly through an adjustment rule that ties repurchases (or the right to make new purchases) to individual permit holdings. Recall that holding permits and adopting a new technology are substitute investment strategies for the firm; thus, any policy that ties individual adjustment to existing permit holdings necessarily links that adjustment to the technology choice, and hence has the potential to distort that choice.

The second additive term in expression (5) captures a "price effect" of the supply adjustment policy on investment incentives. The particular rule used to adjust the supply of permits in period 2 must, in equilibrium, feed back into the expected value of all permits carried forward into period 2, whether or not they are repurchased. The second term in (5) reflects this effect. In particular, if the supply adjustment policy causes the value of a permit carried into period 2 to differ from its true social value in period 2 (that is, $v_j \neq d_j$), then the difference in the permit holdings carried forward under the two technologies (that is, $e_{10}^* - e_{11}^*$) will have a private value different from their true social value. The second term in (5) represents this difference between the private and social value of permit holdings carried forward. It arises through the effect of the anticipated supply adjustment rule on the equilibrium price of permits in period 1.

If $PB^* \neq SB$ then each firm has an incentive to deviate unilaterally from the social optimum. In particular, if $PB^* > SB$ then private incentives are distorted in favour of the new technology. Conversely, if $PB^* < SB$ then the investment decision is biased towards retaining the old technology. If the wedge between PB^* and SB is sufficiently large, such that $PB^* > K > SB$ or $PB^* < K < SB$, then the social optimum is not supported as a rational expectations equilibrium.

Expression (5) can be used to examine the incentive effects of a variety of supply adjustment polices. I confine specific consideration to two alternative policies: open market operations; and a proportional adjustment rule. The analysis of each policy is complicated and I present here only a summary of the main results. First, open market operations, whereby the regulator buys or sells permits as needed at the market price, implements an efficient solution with respect to the choice of emissions in each period and with respect to cleaner technology adoption decisions. However, this supply adjustment policy is unlikely to be politically acceptable because it rewards firms with a windfall gain if the damage caused by their emissions turns out to be worse than expected.

The alternative adjustment rule is a proportional adjustment rule one under which the regulator expropriates a fixed share of permits from each firm if the supply of permits must be reduced, and grants additional permits on a proportional basis if the supply must be increased. The price paid for expropriated permits and the price charged for additional permits granted can be set independently from the supply adjustment to satisfy the distributional goals of the policy maker. The key property of this proportional adjustment rule is that it implements efficiency, both in terms of emission levels and in terms of technology choices. Thus, the proportional adjustment rule delivers the same efficiency advantages of adjustment through market operations but at the same time provides much greater flexibility from a political perspective.

MANAGEMENT APPLICATIONS

The results of this research project have most direct application to the management of forest products processing, including saw milling and pulp and paper production. While harvesting practices are often the most visible and controversial element of sustainable forest management, the environmental impacts of product processing are considerable. An integrated approach to sustainable forest management must include the appropriate management of these impacts. The results of this project provide policy direction with respect this management requirement. In particular, the results offer guidance as to how different regulatory mechanisms are likely to influence investment decisions with respect to the adoption of less polluting technologies. While regulatory pressure is not the only source of incentives in this regard - the demand for sustainably produced products in the marketplace is increasing providing additional incentives -

the role of regulation is an important one. The central message of this research project is that the pricing of pollution, through mechanisms like pollution taxes and tradeable pollution permits, is likely to be the best approach to regulation. Pricing provides short run incentives to reduce pollution based on currently employed technology, and at the same time creates long run incentives for the adoption of new, cleaner technologies. If these pricing policies are designed well - according to the principles delineated in the results of this research project - then they can induce an optimal balance between the benefits of reduced environmental impact and the costs of switching to cleaner technologies. Achieving that balance is crucial to sustaining the boreal forests and at the same time sustaining the economic benefits derived therefrom.

CONCLUSION

The paper has reported on the results of the Incentives for Pollution Control project. I have outlined the analyses and results of two theoretical investigations into the incentives for the adoption of cleaner technologies. The first examines the incentive effects of pollution taxes and tradeable pollution permits. The second examines the optimal design a permit trading system in the presence of uncertainty about environmental impacts and the evolution of information over time. The results of the research delineate principles for the design of these policy instruments to ensure that they induce an optimal balance between the benefits of reduced environmental impact and the costs of new technology adoption.

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