Double Dipping in Pollution Markets

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Abstract: We explore the efficiency of allowing participants in transferable-rights programs to sell credits in multiple markets, i.e., to double dip. In a first-best economy double-dipping is efficient, but if the cap is set suboptimally, then the answer depends on the relative slopes of the marginal benefit and marginal cost curves.

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I. Introduction

Market-based approaches to environmental management are expanding at a remarkable rate. Driven by the simple intuition that it makes sense to minimize the cost of pursuing environmental improvements, since the early 1990s a wide range of programs have been established that differ in an important way from the traditional “command-and-control” approach. In what we will call “market-based” approaches, a regulatory mechanism exists that allows environmental harm at one point to be offset through environmental improvements elsewhere. Such programs may take a variety of forms, from a pure market in which uniform credits are traded at a market-determined price, to offset programs in which the agency gives regulated parties flexibility to comply with regulations by offsetting damages at other locations.

Market-based (MB) approaches are being applied to a wide range of environmental problems; the highly visible SO_2 trading program is but the tip of the iceberg. Air pollution trading ranges from California’s Reclaim program to the multi-state Ozone Transport Commission. In the water pollution arena, a recent report to the U.S. Environmental Protection Agency (EPA) lists sixteen programs in various stages of implementation and nine more programs under development (Environomics 1999). MB elements appear in wetland mitigation banking, in Habitat Conservation Plans that can be used to comply with the Endangered Species Act, in transferable development rights programs, in climate change policies, and virtually every new environmental policy in the U.S. Table 1 presents an extensive list of environmental goods and service that are either covered by MB programs or are under consideration.

As the number of market-based programs grows, so does the potential for interaction among the programs. As a result, there is a rising interest in the concept of *multiple markets* (e.g., Kieser & Associates), the notion that generators of environmental credits might be able to sell credits in many markets, what we will call *double dipping*. If double dipping is allowed then the returns to those that generate environmental credits are increased, providing greater incentives to the most environmentally effective projects. On the other hand, if one project sells credits in two markets, then this means that some other project is unable to sell any credits and may, therefore, go unimplemented. Hence, it is not immediately obvious that allowing double dipping will be socially efficient.

In this paper we explore the issues that arise when considering multiple markets. We begin with a straightforward analysis building on Montgomery of multiple rights markets when there are caps placed on each such pollutant. In this case, it follows immediately that allowing double-dipping will achieve the efficient allocation of the pollution rights. Building on this framework we show that when pollution credits are generated as a joint product, it may be that the price of some rights might go to zero. This adds a new twist to the standard policy advice that the socially efficient level of abatement is where the marginal benefit is equal to the marginal cost. This leads us to the complete planner's problem in which we also consider the societal benefits of pollution abatement. This problem is considered in both a first-best and second-best economy. In the first-best case, we again find that double-dipping leads to the optimal solution. However, in a second-best setting in which the caps are set using a pollutant-by-pollutant standard, the results are mixed and double-dipping may not be socially optimal. The paper concludes with a discussion of problems for future investigation.

II. Literature

Dales (1968a, 1968b) and Crocker (1966) are credited with coming up with the idea of pollution permits to control pollution. The first formal treatment of this problem was provided by Montgomery (1972). As we discuss below, Montgomery's model incorporated the general features of a multiple pollutant problem, although he characterized it as a single pollutant with multiple receptor points.

Montero (2001) is the first author to carefully analyze a problem similar to that we consider here. Montero considers the question as to whether cross-pollutant trading should be allowed, i.e., whether a firm should be allowed to increase emissions of pollutant A by buying credits generated by reducing pollutant B. Although this may seem to be a regulatory impossibility, in the context of a social planner's problem where both pollutants impose social costs, it is appropriate to ask what would be the optimal mix of pollution reduction across the pollutants. Cross pollutant trading with the appropriate trading ratio could yield the optimal allocation. In a fashion akin to Weitzman (1974), Montero finds that the relative slopes of the marginal benefit and marginal cost curves prove critical to determining if cross-pollutant trading should be allowed or not. If the marginal damage curves are steep, then it is inefficient to allow cross pollutant trading.

The issue of double-dipping is particularly important in programs in which there is not a hard cap on aggregate pollution. As highlighted by Dewees (2001), many of pollution trading programs do not have caps. Instead, a source obtains a credit by reducing emissions below its historic levels generating an emission reduction credit (ERC). Interest in the use of ERCs is rising since such instruments can be used to control sources that are not typically regulated so that implementation of a cap is problematic. For example, ERCs are used to reduce nonpoint source pollution (Woodward, Kaiser and Wicks), or to offset wetland losses. The idea of taking advantage of multiple markets is receiving substantial attention in ERC programs (Kieser & Associates). For example, a created wetland might reduce nutrient runoff, sequester carbon and provide habitat for species: four environmental services are provided and quadruple-dipping could generate substantial revenue to the landowner.

For ERC type programs, there is a great deal of attention to the issue of *additionality*, i.e., a credit is only *real* if it is in excess of what the firm would otherwise be providing. When multiple markets are in place, this becomes extremely difficult. For example, a firm that establishes a containment pond to create nutrient credits might also be creating a wetland that provides habitat for water-fowl. If someone nearby needs to offset wetland loss, should the containment pond also be allowed to count for that? Would this second transaction be permitted? From a cost minimization perspective be permitted the answer is, "Probably yes." From a social efficiency perspective the answer is, "Perhaps no".

III. Multiple cap-and-trade markets to achieve cost efficiency

We begin our analysis of multiple pollution rights markets building on the familiar model of Montgomery (1972). Montgomery considered the use of transferable permits for the case of a market in which firms, i=1,…,n, emit a single pollutant, e_i, which is dispersed to m receptors according to the dispersion coefficients h_{ij}. Licenses, l_{ij}, in this case place a cap on the i^{th} firm's emissions of the j^{th} pollutant. The firm's initial allocation of permits is denoted l_{ij}^0.

Define $F_i(e_{i1},...e_{im})$ as the i^{th} firm's cost of reducing emissions to a particular level, i.e., the difference between the firm's profit at the unconstrained maximum, and the profits that can be achieved given that emissions are reduced to $e_{i1},...e_{im}$. Following Montgomery, we assume that $F(\cdot)$ is strictly convex. The problem of each firm is to minimize its cost of emission reduction, $F(\cdot)$, plus license its cost, $l_{ij} - l_{ij}^0$, subject to emission constraint, and positivity conditions as follows:

$$\underset{e_{ij},\, l_{ij},\, \forall j}{Min}\ F_i(e_{i1},...e_{im}) + \sum_{j=1}^{m} p_j (l_{ij} - l_{ij}^0)$$

$$subject\ to\ e_{ij} \le l_{ij},\ \forall j$$
$$e_{ij} \ge 0,\ l_{ij} \ge 0,\ \forall j$$

where p_j is the price for the j^{th} pollution license*,* which is defined in the market.. We assume zero transaction costs.

A market equilibrium can be defined as solution vectors of the above minimization problem for all *i*, e_{ij}^*, l_{ij}^*, such that the following market clearing conditions are also satisfied:

$$\sum_{i=1}^{n} (l_{ij}^* - l_{ij}^0) \le 0,\ \ p_j^* \left[\sum_{i=1}^{n} (l_{ij}^* - l_{ij}^0) \right] = 0,\ \forall j\ .$$

Now, the social cost minimum that is efficient is obtained by solving a following social problem.

$$\underset{e_{ij},\, \forall i, j}{Min} \sum_{i=1}^{n} F_i(e_{i1},...e_{im})$$

$$subject\ to \sum_{i=1}^{n} h_{ij} e_{ij} \le l_j^0,\ \ \forall\ j$$
$$e_{ij} \ge 0,\ \forall i, j$$

Following Montgomery, from this individual firm and social planner's problem, we can have the following lemmas. All proofs are provided in the appendix.

Lemma 1: A market equilibrium of the license market exists for $l_j^0 = \sum_{i=1}^{n} l_{ij}^0$

Lemma 2: Any emission vector $(e_{11},...,e_{nm})$ that satisfies the market equilibrium conditions with $\sum_{j=1}^{m} l_j^0 = L^0$ is a social cost minimum.

As in the single pollutant, multiple locations case considered by Montgomery, Lemmas 1 and 2 establish that a pollution trading market can lead to a cost-minimizing equilibrium if a cap exists for all pollutants and all pollutants are traded. Under the assumptions maintained here, it also follows that the initial allocation of rights does not affect the final allocations or the price of the pollution licenses:

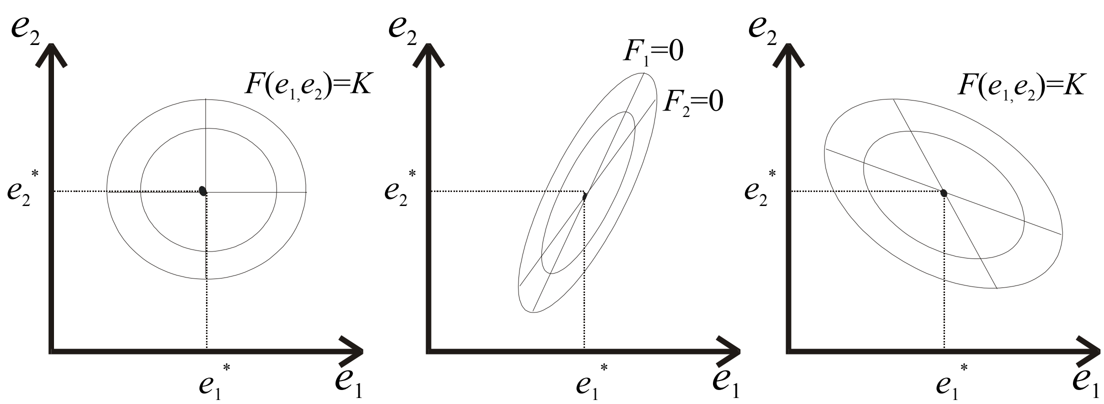
Lemma 3: If $l_{ij}^0 \geq 0$ *and* $\sum_i l_{ij}^0 = l_j^0$, then, vectors of emission, price and license demand for firm *i*, $(e_{i1}^*,...e_{im}^*)$, $(p_1^*,...p_m^*)$, $(l_{i1}^*,...l_{im}^*)$, are independent of initially distributed license vector to firm *i*, $(l_{i1}^0,...l_{im}^0)$.

We find, therefore, that multiple markets can achieve the cost-minimizing allocation of rights across producers. This result is not surprising, but we did not find similar results anywhere else in the literature.

We should note that the assumption of convexity in the cost function in this case is more restrictive than in the single-pollutant case though it remains intuitively plausible. If two pollutants are under consideration, the cost function is convex if the it has a bowl-like shape, with the slope increasing as the firm's pollutions differ from the unconstrained optimum. Convexity of the cost function implies that for any price vector, $P=\{p_1,\ldots,p_m\}$, there is a unique point at which $DF(\cdot)=P$, where DF denotes the gradient of F. Hence, there is a unique global maximum to the firm's optimization problem.

A. Graphical analysis of the firm's problem in a multiple-market setting

In a fashion similar to Helfand (1991), in Figure 1 we present the iso-cost curves associated with differing levels of the two pollutants for a representative firm. The ellipses in the figures indicate combinations of e_1 and e_2 that yield equal costs to the firm relative to the profit maximizing levels of emissions, e_1^* and e_2^*, where $F_1=F_2=0$. Along the lines traversing the ellipses the marginal cost of reducing the pollutants independently are equal to zero. These lines indicate, therefore, the reaction functions of the firm's emissions of one pollutant to restrictions on the other pollutant. In Figure 1a, these reaction curves are horizontal and vertical, so that the optimal levels of emissions of the two pollutants are independent of the emissions of the other pollutant. In the b and c, however, the cost-minimizing level of emissions of the pollutants are related to the emissions of the other pollutant. In Figure 1b the pollutants are complements – if the firm is forced to reduce e_1, then to minimize costs it will also reduce e_2. In Figure 1c, on the other hand, the pollutants are substitutes – a requirement to reduce e_1 will lead the firm to increase its emissions of e_2.



(a) **(b)** **(c)**

Figure 1

As can be seen in Figure 1, the relationship between the two emissions in the firm's cost function is central to determining the optimal emissions. Moreover, the marginal cost of reducing emissions is critically dependent upon the full set of emissions. In Figure 2 we present the case of a firm that faces a tradeable permits program on pollutant 1 at price p_1. This price on its emissions of e_1 cause it to reduce its emissions from e_1^* to $\underline{e}_1$, where $F_1=p_1$.

But what is the marginal cost of reducing e_2? There are three points that might be considered. Because e_1 and e_2 are complements, cost-minimizing behavior leads the firm to reduce emissions of e_2 as well, by a_2 from e_2^* to $\hat{e}_2$, where F_2=0. If the marginal cost were evaluated at $\underline{e}_1$, e_2^*, i.e., the original level for e_2 and the new level for e_1, the marginal cost of reducing emissions of 2 is actually negative – costs go down by reducing e_2. If the marginal cost of reducing e_2 were evaluated at the new level for e_2, $\hat{e}_2$, but at the original level of e_1, e_1^*, then it would appear that the marginal cost of reducing e_2 would be positive. When pollutants are joint products, then when evaluating the marginal cost of controlling any one pollutant it is important to consider the levels of all other pollutants.

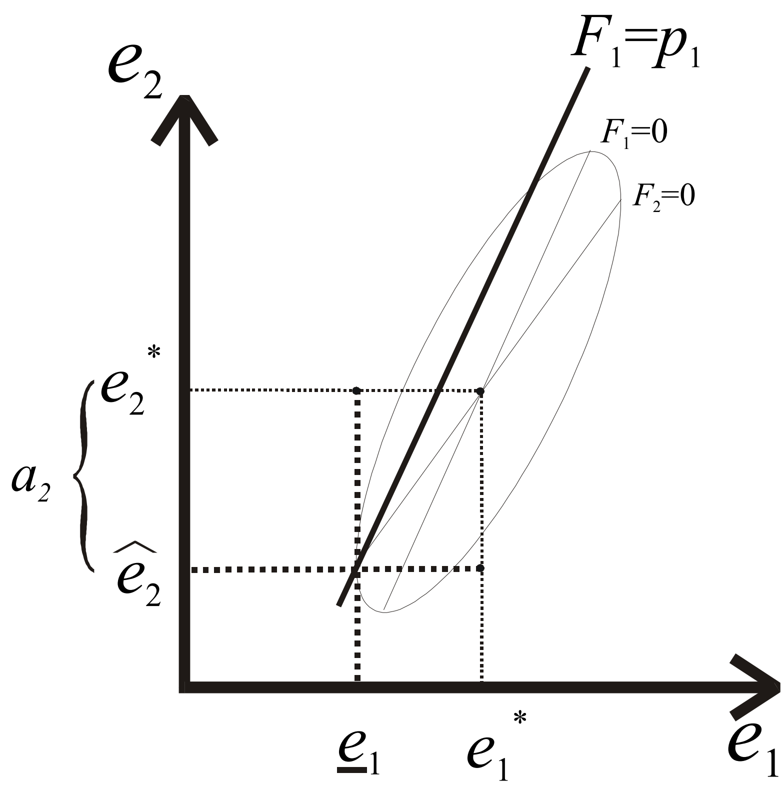


Figure 2

IV. Social efficiency and multiple cap and trade programs

Following the Montgomery model, we have seen that when multiple pollutants are emitted, allowing for multiple emissions trading programs can identify the cost-minimizing allocation of emissions. In this section we consider the relationship between multiple markets and the socially efficient level of emissions. The conclusion is quite straightforward: the socially optimal level of pollution reduction is achieved by allowing multiple markets, but the cap on pollutants should reflect this. As we show in the section that follows, however, the optimality of allowing double-dipping is dependent on the aggregate caps being set at their optimal levels.

Define a firm's emission abatement, a_{ij}, as the difference between e_{ij}^* and actual emissions e_{ij}, i.e., $a_{ij}=e_{ij}^*-e_{ij}$. Aggregate abatement of the j^{th} pollutant is written $A_j = \sum_i a_{ij}$. The industry costs are simply the sum across all firms: $TC = \sum_i F\left(e_{i1},\ldots,e_{im}\right) = \sum_i g_i\left(a_{i1},\ldots,a_{im}\right)$. Our focus here is on the interactions between the pollutants in the firms' cost functions, hence we assume that the social benefits of abatement are additively separable and that, since all pollutants are assumed to be uniformly dispersed, are functions of aggregate abatement: $TB = \sum_j B_j\left(A_j\right)$. [1] The planner's problem, therefore, is to maximize total net benefits:

$$\max_{\{a_{ij}\}} \sum_j B_j\left(A_j\right) - \sum_i g_i\left(a_{i1},\ldots,a_{im}\right).$$

At the optimum, for all pollutants the marginal cost of abatement must be equal across firms, $G_j' = \frac{\partial g_i(\cdot)}{\partial a_j} = \frac{\partial g_k(\cdot)}{\partial a_j}$ for all *i*, *k*. The optimal cap will be set at a level where the marginal benefit equals the marginal cost, $B_j' = G_j'$ for all *j*. If the caps for all pollutants are set simultaneously at the optimal levels, then by Lemma 2, a multiple-markets program in which sources are able to trade credits in all pollution credit markets will lead to the social optimum.

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[1] There has been some attention to cases where pollutants jointly interact in the environment (e.g., Schmieman, 2002).

A. Social optimum for fixed-coefficient technology

As an interesting example, consider the case which m=2 and the firms' abatement of the two pollutants occurs in fixed proportions, i.e. $a_{i1}=\gamma_i a_{i2}$, for all i. In this case the optimization problem becomes,

$$\max_{e_{11},e_{12},e_{21},e_{22}} B_1\left(\sum_i a_{i1}\right)+B_2\left(\sum_i a_{i2}\right)-\sum_i g_1\left(a_{i1},a_{i2}\right).$$

Because abatement occurs in fixed proportions, we can rewrite the a_{i2} in terms of a_{i1} and the cost functions, $g(\cdot)$ can be expressed in terms of a single argument, say $g_i\left(a_{i1},\gamma_i a_{i2}\right)=\tilde{g}_i\left(a_{i1}\right)$. When $a_{i2}=\gamma_i a_{i1}$, $\frac{\partial g_i\left(\cdot\right)}{\partial a_{i1}}=\frac{\partial \tilde{g}_i\left(\cdot\right)}{\partial a_{i1}}$, and $\frac{\partial g_i\left(\cdot\right)}{\partial a_{i2}}=\gamma_i\frac{\partial \tilde{g}_i\left(\cdot\right)}{\partial a_{i1}}$.

The first order conditions of the planner's problem for a_{i1} is

$$B_1'+\gamma B_2'-g_{i1}'=0.$$

What is significant here is that the optimal level of total abatement is set *not* where $B_j'=g_i'$; because of the joint production of a_1 and a_2, the benefit across both pollutants must be taken into account.

If an aggregate abatement goal were set where the marginal cost equals the marginal benefit on a pollutant by pollutant basis then suboptimal pollution abatement would be sought. Yet, standard guidance for policy has been to abate pollution up to the point where the marginal benefit equals the marginal cost. To the extent that any criterion of optimality is being sought in such policies, it is very likely that pollutant-by-pollutant standards are being used, hence a second-best approach in which it is assumed that the policy is based on suboptimal caps.

V. Multiple markets in a second-best economy

For our analysis of multiple markets in a second-best setting, we consider a very simple case presented in Figure 3. We assume that some polluters emit two pollutants and that regulation of e_1 leads to abatement of a_2 by those firms as in Figure 2 above. The marginal cost of abatement for the remaining firms is represented by the curve MC_2 in Figure 3. The true social marginal cost curve, MC^*, takes into account the "free" abatement of a_2. Hence, the socially optimal level of abatement of pollutant 2 is $\overline{A}_2^*$, where the social marginal cost equals the social marginal benefit, $B'(A_2)$. On the other hand, if policy is mistakenly set without taking into account the abatement that takes place as a result of regulations on pollutant 1, then it the level chose would be $\overline{A}_2$, where $MC_2 = B'(A_2)$.

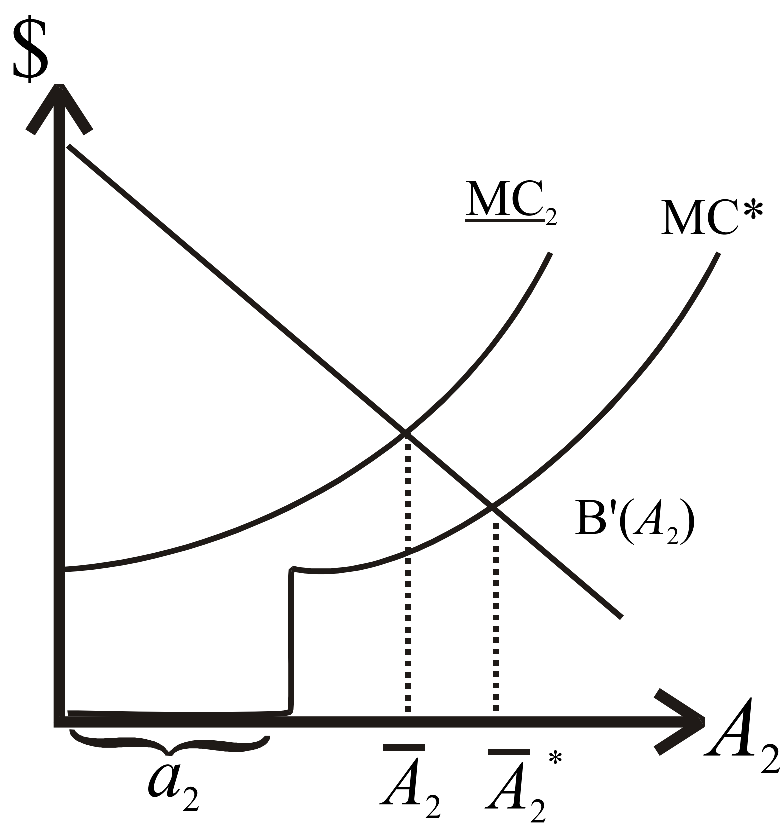

Figure 3

As noted above, if the cap is set at $\bar{A}_2^*$, then it is efficient to allow double-dipping. If the cap is set inappropriately at $\bar{A}_2$, however, then this is not so clear. To answer this question we turn to Figure 4. Note that regardless of whether double-dipping is allowed, the a_2 units of abatement created by the regulation of pollutant 1 will take place and will yield social benefits. If multiple markets are not allowed, then the remaining firms must supply $\bar{A}_2$ units of abatement, leading to total abatement of $\bar{A}_2 + a_2$. If double-dipping is allowed, then only $\bar{A}_2$ units of abatement would be provided, with $\bar{A}_2 - a_2$ units supplied by the firms not presented in Figure 2.

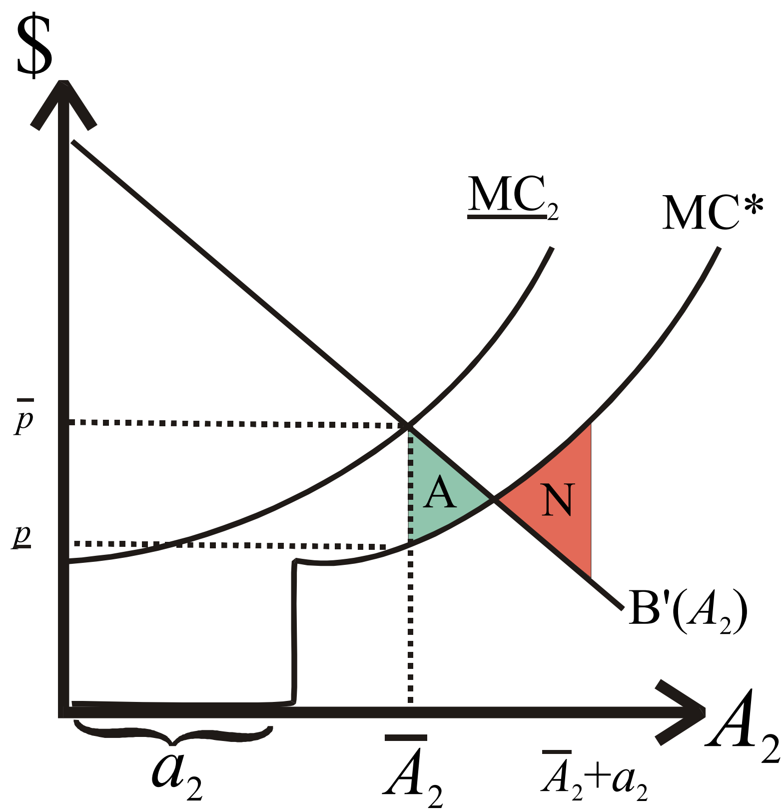

Figure 4

Because $\bar{A}_2$ is not socially optimal, a welfare loss will result; the question is whether the loss is greater with or without double-dipping. This question is analyzed using Figure 4. If double-dipping is allowed, then total abatement will be $\bar{A}_2$ and the equilibrium price in the market will be at $\underline{p}$. The welfare loss associated with allowing multiple markets in this case is the shaded triangle marked A, that results because from $\bar{A}_2$ to $\bar{A}_2^*$ the marginal benefits exceed the marginal costs. The alternative is to not allow double-dipping. In this case the a_2 credits would not be counted in the pollutant 2 market and total abatement would be $\bar{A}_2 + a_2$. In this case total abatement is in excess of the optimal level and from $\bar{A}_2^*$ to $\bar{A}_2 + a_2$ the marginal benefits are less than the marginal costs, as indicated by the by the shaded triangle labeled N.

In this simple example, the efficiency of allowing for multiple markets depends on the relative slopes of the MC and B' curves. If B' is relatively steep, then the N triangle grows implying that it is more inefficient to not allow double-dipping. Intuitively, this makes sense since a steep B' curve indicates that total abatement goal is fairly well defined, and multiple markets allow us to achieving that goal at the lowest possible cost. On the other hand, if B' is relatively flat, then the total abatement goal is not so well defined but is quite sensitive to the marginal cost. For flat B' curves the triangle A grows and the triangle N shrinks. In this case, allowing multiple markets would be more inefficient. At the extreme, if the marginal benefit curve is horizontal, then it clearly holds that it is inefficient to allow double dipping.

VI. Discussion, conclusions, and future research

We have seen that the question of whether firms should be allowed to sell credits in multiple markets is not as straightforward as might typically be assumed. If caps are set optimally, then it is clear that double-dipping provides optimal incentives and will lead to the first-best outcome (at least in the deterministic setting with a perfectly functioning market that we assume). However, setting caps optimally is not straightforward. Policies are frequently handled in a rather piecemeal fashion; global warming goals are separate from nutrient criteria, which are separate from wetlands requirement. If caps are set in this piecemeal fashion, then to the extent that any optimization criteria is used to set the caps, it will probably be done where the marginal benefits of abatement equal the marginal cost of abatement, without taking into account how the various policies interact.

If abatement targets are set using this second-best criterion, then it is no longer automatic that allowing multiple markets is appropriate. As we show graphically, there are situations where the welfare loss can be lower without multiple markets than they are with multiple markets. It is not always efficient to allow double-dipping. In particular, we find it interesting that as the marginal benefit curve becomes flat, relative advantage of double-dipping falls. Hence, although our analysis is quite preliminary, we believe that it may be inappropriate to allow double-dipping in the provision of greenhouse-gas credits because in diminishing this global externality, the marginal benefit of the sequestration on any one acre is likely to be essentially constant over a very large range.

Our analysis so far is quite limited. An analytical and/or numerical exploration of this issue is needed and is being pursued. We need to be more precise in establishing the conditions under which double-dipping is and is not efficient. This will provide more robust analysis for policy makers as they consider the changing landscape of market-based environmental policy.

Environmental good or service	**Currency**	**Regulatory Driver**
Wetland	Acres	Federal & State
Stream	Linear feet	Federal & State
Buffer	Acres	State
Habitat	Species/habitat acreage	Federal & State
Forest	Acres	State
Carbon/Greenhouse Gases	Tons of CO_2 emissions	State & (possibly) Federal
Nutrients	Pounds	State
Miscellaneous water quality	Pounds	Federal & State
Stormwater	Acres of pervious cover	Federal & State
Renewable energy	Renewable energy credits	State
Water rights	Acre-feet of water	State
Aquifer recharge	Acres of pervious cover	State
Development rights	Development or density units	County

Table 1: Range of types of environmental credits in use or under consideration.
Source: Based on George Kelly, Environmental Banc & Exchange. Presentation to The EPRI Environmental Sector Council, Sept. 10-12, 2003

VII. Appendix: Proofs

Assuming that the $F(\cdot)$ is strictly convex, the firm and planner's problems are convex programming problems so that the Kuhn-Tucker conditions are necessary and sufficient conditions for an optimum. The Lagrangian of the firm's minimization problem is

$$L(e_{i1},...e_{im},l_{i1},...l_{im},u_{i1}..u_{im}) = F_i(e_{i1},...e_{im}) + \sum_{j=1}^{m} p_j(l_{ij} - l_{ij}^0) - \sum_{j=1}^{m} u_{ij}(l_{ij} - e_{ij})$$

Given an equilibrium price vector, p_j^*, an optimum of vector of choices and shadow prices, e_{ij}^*, l_{ij}^*, u_{ij}^*, satisfies the following first-order conditions,

$$(2)...[F_{ij}^{'}(e_{i1}^*,...,e_{im}^*) + u_{ij}^*] \geq 0,\ e_{ij}^*[F_{ij}^{'}(e_{i1}^*,...,e_{im}^*) + u_{ij}^*] = 0$$

$$(3)...(p_j^* - u_{ij}^*) \geq 0,\ l_{ij}^*(p_j^* - u_{ij}^*) = 0$$

$$(4)...(l_{ij}^* - e_{ij}^*) \geq 0,\ \ u_{ij}^*(l_{ij}^* - e_{ij}^*) = 0$$

The price vector will be a market clearing if the following conditions are satisfied:

$$(5)...\sum_{i=1}^{n}(l_{ij}^* - l_{ij}^0) \leq 0,\ \forall j\,,$$

$$(6)...p_j^*\left[\sum_{i=1}^{n}(l_{ij}^* - l_{ij}^0)\right] = 0,\ \forall j\,.$$

The social planner's cost minimum is the vector of e_{ij}^* that solves the following problem:

$$(7)\ \ \underset{e_{ij},\forall i,j}{Min} \sum_{i=1}^{n} F_i(e_{i1},...e_{im})$$

$$subject\ to \sum_{i=1}^{n} e_{ij} \leq l_j^0,\ \forall\ j$$

$$e_{ij} \geq 0,\ \forall i, j$$

The Lagrangian for this minimization problem is

$$L(e_{11},...,e_{nm},u_1,...,u_m)=\sum_{i=1}^{n}F_i(e_{i1},...,e_{im})-\sum_{j=1}^{m}u_j(l_{ij}^0-\sum_{i=1}^{n}e_{ij})$$

$(e_{i1}^*,...,e_{im}^*)$ for all i is a social cost minimum if and only if there exists $(u_1^{**},...,u_m^{**})\geq 0$ such that the following Kuhn-Tucker conditions for all *i and j* are*:*

$$(8)...[F_{ij}^{'}(e_{i1}^{**},...,e_{im}^{**})+u_j^{**}]\geq 0,\quad e_{ij}^{**}[F_{ij}^{'}(e_{i1}^{**},...,e_{im}^{**})+u_j^{**}]=0$$

$$(9)...l_j^0-\sum_{i=1}^{n}e_{ij}^{**}\geq 0,\quad u_j^{**}(l_j^0-\sum_{i=1}^{n}e_{ij}^{**})=0$$

[Proof of lemma 1] Let e_{ij}^{**}, u_j^{**} be optimum choices for the planner's problem, satisfying equations (8) and (9), for some total load limit, L_j^0, *j*=1,…,*m*. Let p_j^*, e_{ij}^*, u_{ij}^*, l_{ij}^* be the satisfying the optimum conditions for the market equilibrium, equations (2) through (6).

If we substitute e_{ij}^{**}, u_j^{**} into (2) instead of e_{ij}^*, u_{ij}^*, the equation (2) becomes equivalent to equation (8) so that e_{ij}^{**}, u_j^{**} satisfy the equation (2).

Equation (3) is satisfied for all *i* and *j* if $p_j^*=u_j^{**}$, $u_{ij}^*=u_j^{**}$.

Equation (4) is also satisfied for all *i* and *j* because $l_{ij}^*=e_{ij}^{**}$, $e_{ij}^*=e_{ij}^{**}$

Equation (5) becomes $\sum_{i=1}^{n}(h_{ij}e_{ij}^{**}-l_{ij}^0)\leq 0$ since $l_{ij}^*=e_{ij}^{**}$. This is immediately equivalent to the left equation of (9) since we defined $l_j^0=\sum_{i=1}^{n}l_{ij}^0$.

Equation (6) is equivalent to the right equation of (9) since

$p_j^*=u_j^{**}$, $l_{ij}^*=e_{ij}^{**}$, $l_j^0=\sum_{i=1}^{n}l_{ij}^0$.

The social cost minimum, e_{ij}^{**}, u_j^{**}, satisfy the market equilibrium generated from the individual firm's optimization problem given the market price.

Since this is satisfied for an arbitrary load limit, L_j^0, it holds for any feasible limit.

[Proof of lemma 2] Now, let's define the solution of (8) and (9) as $u_j^{**} = p_j^*, e_{ij}^{**} = e_{ij}^*$. If we substitute the solution p_j^*, e_{ij}^* into (8) and (9) instead of u_j^{**}, e_{ij}^{**} respectively and this solution satisfies the equation (8) and (9), then the lemma 2 is proved.

By substitution, the left side of equation (8) becomes $[F_{ij}^{'}(e_{i1}^*,...,e_{im}^*) + p_j^*] \geq 0$, which is shown from the left side of equation (2) because $p_j^* \geq u_{ij}^*$ from the left side of equation (3).

As for the right side of equation (8), if $p_j^* > u_{ij}^*$, then, $l_{ij}^* = 0$ from the equation (3) and $e_{ij}^* = 0$ from the left side of equation (4), which, in turn, satisfy the right side of equation (8) by substituting $e_{ij}^* = 0$ instead of e_{ij}^{**}. If $p_j^* = u_{ij}^*$, combined with $u_j^{**} = p_j^*$, $e_{ij}^{**} = e_{ij}^*$, the right side of equation (8) becomes equivalent to the right side of equation (2).

The left side of equation of (9) is achieved by $e_{ij}^{**} = e_{ij}^*$: Let's sum the left side of equation (4) over *i*, and add this with equation (5) after changing its sign to be positive. We can obtain $l_j^0 - \sum_{i=1}^{n} e_{ij}^* \geq 0$ with the definition of $l_j^0 = \sum_{i=1}^{n} l_{ij}^0$, which is equivalent to (9) when we replace $e_{ij}^{**} = e_{ij}^*$ in (9).

As for the right side of equation (9), if $l_{ij}^* > e_{ij}^*$, then, $u_{ij}^* = 0$ from the equation (4) and $p_j^* = 0$ from equation (3). Therefore, the right side of (9) is satisfied since $u_j^{**} = p_j^*$. If $l_{ij}^* = e_{ij}^*$, equation (9) becomes the same as (6) when $u_j^{**} = p_j^*$.

[Proof of lemma 3] Equations (2) – (4) do not depend on $(l_{i1}^0,...l_{im}^0)$. Equation (5) only depends on $(l_1^0,...l_m^0)$, but not on $(l_{i1}^0,...l_{im}^0)$.

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