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With Discrete Abatement Units

By

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Abstract: This paper answers three questions related to the discrete nature of pollution abatement: (i) does a source's incremental control cost (as defined by the U.S. Environmental Protection Agency) necessarily exceed its average control cost, (ii) is incremental control cost a better approximation of a source's willingness to pay for abatement credits than average control cost, and (iii) exactly how does trading in discrete and continuous abatement markets differ? We find that the answer to the first two questions are both "no", suggesting that the U.S. Environmental Protection Agency needs to refine its reliance on incremental control cost as the sole measure upon which to assess the financial feasibility of water quality trading. In answer to the third question, we show that the outcome of bilateral trading in the presence of discrete abatement is determined by comparing the gains from trade associated with the full sequence of possible "sunk cost trading" scenarios. For the most common case where trading partners' average control cost curves "cross," the trading outcome with discrete abatement is inherently sensitive to the initial allocation of abatement responsibilities.

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1. Introduction

According to the United States Environmental Protection Agency (EPA), the first step in assessing the financial attractiveness of water quality trading (WQT) in any given watershed is to calculate dischargers' incremental costs of control (IC) [EPA, 2004].[1] This is because IC, defined as the average cost of control *of the incremental reduction required for a discharger to achieve its target load*, represents a better approximation of a discharger's, or source's, upper-bound willingness to pay (WTP) for pollutant reduction credits.[2] The logic behind this statement is that each control "step", once implemented, is a sunk cost. If a source had previously installed a control technology, its expense should not influence the next step decision for pollutant control. As the EPA puts it, "if a source implements step 1 control technology and is now looking toward a step 2 option, the IC considers only the cost of the second step of control technology; the previous step cost is sunk and is no longer part of the decision making analysis" [EPA , 2004, page 34].

This paper takes a close look at IC in the context of discrete, or discontinuous abatement. In particular, the relationships between IC and both the traditional measure of average cost of control (AC) and WTP is examined.[3] Three questions about these relationships are answered. First, is IC necessarily larger than AC, i.e., is it necessarily a better approximation than AC of upper-bound WTP? Second, is IC a better approximation than AC of WTP itself? Third, does the initial allocation of abatement

[1] The referenced document, *Water Quality Trading Assessment Handbook*, is the EPA's central document on WQT, particularly with respect to the promotion of WQT throughout the United States.
[2] Subtracting the source's target load from its current load results in the source's total reduction needed to comply with its Total Maximum Daily Load (TMDL) abatement allocation. As far as this author is aware, EPA [2004] is the only published document that discusses the IC as defined therein. Magat, et al. (1986) consider a different type of IC, the calculation of which is based on the incremental reduction *actually achieved*, rather than *required*. As shown below in Sections 3 and 4, the Magat, et al. (1986) definition of IC is equivalent to what we have labeled average cost of control (AC) in this paper.
[3] AC is equal to the total cost of a technology step divided by the number of abatement units achieved.

responsibilities in the presence of discrete abatement affect trading outcomes differently than when abatement is continuous? These questions are important because little is presently known about IC and how it compares with AC and WTP. Indeed, if the financial attractiveness of WQT is to be based on IC rather than AC (as suggested by the EPA), it seems imperative to understand exactly how IC and AC differ. This imperative is compounded by the fact that WQT in the US has thus far been rather unsuccessful as a mechanism for meeting water quality standards established through the Clean Water Act (King, 2005; Environomics, 1999). Further, while the pollution trading literature has addressed a wide variety of issues that relate to the feasibility of market establishment, the principle issue of discreteness in abatement units itself has yet to be considered in any theoretical way.[4]

In answer to the first question, we find circumstances under which IC may not exceed AC. In particular, when the initial technology step (step1) is *capable* of meeting or exceeding the source's target load, IC is at least as large as its corresponding AC. However, when technology step 1 is *incapable* of achieving the source's target load, and the source has not previously implemented its step 1 technology, IC exceeds its corresponding AC only when the efficiency of its step 1 technology is large enough relative to its subsequent technology steps. This result is explained in Section 4.

[4] Prominent issues addressed in the pollution trading literature include the identification of optimal trading ratios for non-point sources [Shortle, 1987 and 1990; Malik et al., 1993; Horan and Shortle, 2005; Farrow et al., 2005; Hung and Shaw, 2005], empirical/numerical estimates of cost savings with pollution trading [Fullerton et al., 1997; Bernstein et al., 1994; Hahn and May, 1994; Coggins and Smith, 1993; Bohi and Burtraw, 1992; Atkinson and Tietenberg, 1991; Hahn and Hester, 1989a and 1989b; Hahn, 1989], the roles of transaction costs [Winebrake et al., 1995; Stavins, 1995, Lund, 1993; GAO, 1994; Montero, 1997], market concentration/failure [Cason et al., 2003; Atkinson and Tietenberg, 2001; Misiolek and Elder, 1989; Hahn, 1984; O'Neil, 1983], market size [Atkinson and Morton, 2004], banking [Wen et al., 2005; Germain et al., 2004; Cronshaw and Kruse, 1996], noncompliance [Konishi, 2005; Keeler, 1991], moral hazard [Joskow and Schmalensee, 1986], and price uncertainty [Baldursson and von der Fehr, 2004; Rubin, 2001; Chao and Wilson, 1993].

In answer to the second question, AC is indeed a better approximation than IC of a source's WTP. This is because in the presence of discrete abatement units, AC is identical to traditionally defined marginal control cost (MC). Since in general any source is capable of being a buyer or a seller of pollution reduction credits depending upon its choice of how much to abate relative to its target load, its WTP is ultimately its MC. Thus, by a simple application of transitivity, a source's WTP equals its AC. Moreover, given that IC will not necessarily exceed AC, IC is also not necessarily the appropriate upper-bound WTP.

In answer to the third question, the determination of a trading outcome between two sources in the presence of discrete abatement is markedly different than the corresponding outcome with continuous abatement. The solution process for trading with discrete abatement requires a comparison of the gains from trade associated with the full sequence of possible “sunk cost trading” scenarios in any "move" away from the initial allocation of abatement responsibilities. As demonstrated graphically in Section 5, corner solutions (where one source is paid by the other to abate the entire aggregate amount to meet the sources' target loads) are possible in the most common case, where trading partners' respective AC curves "cross".[5]

Only two previous studies have addressed the issue of discrete abatement, both strictly in the context of numerical analysis and thus as a kind of epilogue to the main thrust of their analyses. As a result, the principle differences between discrete and

[5] The trading outcome between any two sources is not necessarily concomitant with a market equilibrium, i.e., a market could conceivably be in disequilibrium even though a subset of sources have consummated a series of bilateral trades. Our goal here is to compare the likely outcome of a bilateral trading process when abatement is discrete versus continuous. The determination of any particular market equilibrium is beyond the scope of our analysis.

continuous abatement have not been adequately addressed in the literature.[6] Fullerton et al. [1997] find numerical evidence that in the presence of discrete abatement an electric utility's compliance choices (e.g., across options such as fuel switching, investment in abatement technology, and pollution trading) are highly sensitive to slight deviations in the Public Utility Commission's (PUC's) "symmetric regulatory treatment" of shareholder vs. ratepayer portions of the cost of sulfur dioxide permit purchases, the gain on permit sales, the extra cost of fuel, and the cost of abatement technology. For example, a 1% increase in the portion of permit costs shared by shareholders is enough to induce the shareholders to completely eschew the purchase of permits resulting in substantial increases in ratepayer expenditures on electricity. Thus, changes in PUC rules can apparently sensitize an electric utility's abatement effort to its initial allocation of abatement responsibility.

Montero [1997] similarly finds numerical evidence that in the presence of discrete abatement, transaction costs, and uncertain regulatory policy, abatement effort across sources (and thus aggregate control costs and credit price) is sensitive to the initial allocation of abatement requirements, even when marginal transaction costs are constant. As we show in Section 5, a source's abatement effort is sensitive to the initial allocation of abatement responsibilities in the discrete case even without accounting for the types of inefficiencies examined in Fullerton et al. [1997] and Montero [1997].

[6] Nemetz and Drechsler (1979) and Rousseau and Proost (2005) also incorporate discrete abatement technology in their respective numerical simulations, but discreteness is much less of a concern in their analyses. See Halkos (1994) for an example of how discrete abatement is incorporated into a mathematical model for determining cost-effective emissions control strategies subject to varying pollution control targets, and similarly Becker, et al. (1993) for the development of an efficient allocation mechanism in the presence of discreteness.

To establish a benchmark for our analysis, the next section presents the textbook example of pollution trading when abatement units are continuous. Section 3 examines the relationship between IC and AC in the context of a simple numerical example of a watershed. The purpose of this section is to demonstrate exactly how these cost measures are calculated. Section 4 provides a formal comparison of IC and AC, resulting in our first main finding – IC does not necessarily exceed AC and thus is not a universally better measure of upper-bound WTP. Section 5 recasts in discrete units the continuous-unit pollution-trading example depicted in Section 2. This section demonstrates how consideration of the gains from trade associated with a full sequence of possible sunk cost trading scenarios is used to determine a trading outcome when the discontinuous AC curves of any two trading partners cross, and explains our second main finding – that the trading outcome in the presence of discrete abatement is inherently sensitive to the initial allocation of abatement responsibilities. Section 6 concludes.

2. Water Quality Trading with Continuous Abatement Units

It is well-known that in the presence of continuous abatement WQT induces pollution sources to voluntarily trade up to the least-cost abatement allocation. This result is perhaps most easily understood in a graphical framework, as depicted in Figure 1.[7]

[INSERT FIGURE 1 HERE]

Figure 1 shows the MCs for any two sources (1 & 2), where the level of abatement for Source 1(2) increases from 0 to 25 units going left to right(right to left). In this example, a total of 25 units of abatement across these two potential trading sources are required by the regulatory authority; thus the horizontal axis depicts all possible allocations of the 25 required abatement units between the two sources. As depicted in

[7] See Tietenberg [2006] and Kolstad [2000] for further details about this framework.

the figure, Source 2 faces relatively higher control costs than Source 1 per unit reduction. Source 2 therefore has incentive to purchase abatement units from Source 1 whenever a quota established by the regulatory authority allocates anything greater than(less than) 10(15) units of abatement to Source 2(1).[8]

To see why a trade in Figure 1 is mutually beneficial, assume the regulatory agency determines that the two sources must clean up 12.5 units each, i.e., each source's initial abatement allocation is 12.5 units. At this allocation, total variable cost of control for Source 1 equals area A, while for Source 2 it equals area B + C + D. Therefore, for this allocation total variable cost across both sources equals A + B + C + D. An incentive to trade exists for the two sources at this allocation because the marginal cost of control for Source 2 (point *a*) is substantially higher than that for Source 1 (point *c*). Source 2 could therefore lower its control cost by paying Source 1 something less than *a* but greater than *c* to incrementally increase its abatement from 12.5 so that Source 2 can incrementally reduce its abatement from 12.5. In other words, point *a* represents Source 2's WTP for the first increment of reduction obtained from Source 1, and point *c* represents Source 1's minimum willingness to accept (WTA) payment from Source 2 for that unit.

Continuing in this manner, until all gains from trade are exhausted, the least-cost solution is ultimately obtained where the marginal control cost for each source is equated. In Figure 1, this occurs at point *b*, where Source 1 cleans up 15 units and Source 2 ten units, leading to (minimized) total control cost of area A + B + C. In other words, unrestricted pollution trading naturally leads to the least-cost allocation of abatement across the two sources. What helps drive this result is the continuity of abatement, and

[8] Likewise, Source 1 has incentive to purchase abatement units from Source 2 whenever a quota allocates anything greater than(less than) 15(10) units of abatement to Source 1(2).

thus the smoothly increasing MC curves, as well as the absence of inefficiencies such as transaction costs, regulatory uncertainty, and asymmetric regulatory treatment. Moreover, it is easy to see from Figure 1 that regardless of their initial abatement allocations the sources will always have incentive to trade up to the point where their marginal abatement cost curves intersect (at point *b*), i.e., the least-cost solution is independent of, or insensitive to, the initial allocation of abatement responsibilities.[9]

3. An Example of Incremental and Average Control Costs

As mentioned in Section 1, EPA [2004] argues that in the presence of discrete abatement (which typifies reality), IC is an appropriate estimate of MC when assessing the financial attractiveness of WQT, and therefore an approximation of a potential buyer's WTP for abatement credits [EPA, 2004]. To see how IC is calculated, we present hypothetical cost-of-control and control-effectiveness data for total phosphorus (TP) in Table 1.[10]

[INSERT TABLE 1 HERE]

To begin, note that the current loads, target loads, and total reductions needed for each respective source to comply with the watershed's TMDL for TP are provided in columns 2 – 4, which, as explained in EPA [2004], are (ideally) obtainable from the TMDL itself. Next, note that consecutive technology steps are assumed to exist for each source (except for Stinky's and Smelly's Cheese Factories, which have single technology steps). For point sources (PSs) such as WWTFs #1 and #2 and the two cheese factories,

[9] Unless, of course, the initial abatement allocation in Figure 1 by chance happens to be 15 units to Source 1 and 10 units to Source 2, in which case no trading will take place.
[10] The data in Table 1 represents a slightly revised version of that presented in EPA [2004].

these steps are typically referred to as "tiers" [EPA, 2003]. For NPSs, such as Bob's Farm, these steps are different BMPs, e.g., conservation tillage, grass buffer strips, etc.[11]

Each step is associated with incremental and cumulative reductions achieved (columns 5 and 6 in Table 1) and the incremental reduction needed for compliance with the TMDL (column 7), which is calculated as the difference between the TP reduction needed and the incremental reduction achieved. Surplus TP reductions, or credits, are then calculated in column 8 as the difference between cumulative reductions achieved and reductions needed (which is zero if the difference is negative). Total control cost in column 9 (which we henceforth denote as TC_j for j = 1,….,m different possible technology steps) is next, reflecting the annualized fixed, operations, maintenance, and associated opportunity costs of implementing technology step j.[12]

Thus, considering Bob's Farm in Table 1, technology step 1 results in a reduction of 91 lbs. of TP per day at a TC_1 of $49,823. This leaves 255 lbs. of TP (364 lbs. – 91 lbs.) still needing to be reduced. Adding Step 2 technology at a TC_2 of $464,444, results in an additional reduction of 623 lbs. of TP, or a cumulative reduction of 714 lbs. Therefore, with technology steps 1 and 2, Bob's Farm obtains 368 credits (714 lbs. – 364 lbs.) for possible sale in a water quality trading market.

IC in column 10 is then calculated as TC_{j*} divided by the incremental reductions needed for compliance, divided again by 365 (to normalize to a daily basis), where j* represents the technology step at which the source comes into compliance with its TMDL abatement allocation. For example, Bob's Farm's IC of $4.99 /lb./day is calculated as

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[11] For any given source, subsequent technology steps are dependent upon previous steps having been taken, i.e., step 2 cannot be taken until step 1 has been taken.

[12] In particular, TC_j equals the sum of (1) fixed cost of installing technology step j/useful life of technology step j, (2) annual operating and maintenance costs of technology step j, and (3) Opportunity Cost (which equals the sum of (1) and (2) times the market interest rate).

($464,444/255 lbs.)/365 days. As defined in EPA [2004], IC therefore represents the cost per unit reduction that Bob's Farm must incur to ultimately (or incrementally) bring itself into compliance.

IC is unlikely to be a good estimate of a potential purchasing source's WTP. This is because a forward-looking source will always base its WTP on MC, even in the case of discrete abatement.[13] As we show below, given the discrete nature of abatement, MCs are themselves discretely constant (i.e., step-like) over successive technology steps (e.g., we can think of there being successive levels of marginal control costs (MC_j) defined over corresponding ranges of abatement). Further, each MC_j effectively coincides with its corresponding Average Control Cost (AC_j).[14] As we also show in Section 4, IC generally exceeds AC_j, $\forall$j. Thus, a purchasing source's IC exceeds its WTP.

AC_j in column 11 of Table 1 equals TC_j divided by technology step j's corresponding incremental reduction achieved (normalized by 365 days per year). For example, the AC_1 of $1.50/lb./day associated with Bob's Farm's Step 1 technology equals $49,823/91 lbs./365 days. Similarly, the AC_2 of $2.04 associated with Bob's Step 2 technology is equal to ($464,444/623 lbs.)/365 days. Weighted AC in column 12 is a single measure of average control costs, measured simply as the sum of the AC_j's (i.e., $\Sigma_j AC_j$) divided by the total amount of reductions achieved. Continuing with Bob's Farm, its Weighted AC

[13] By "forward-looking" we mean that the potential purchasing source understands that if it instead chooses to abate more than its TMDL abatement allocation it will have credits to sell.

[14] For goods that can be produced in continuous units at constant marginal cost, this coincidence occurs asymptotically. In the case of discrete goods (such as abatement), the coincidence is exact when MC is measured on a per-unit basis. Note that if we do not measure MC on a per-unit basis, MC of the first abatement unit of the first technology step equals TC_1 and MC of all subsequent abatement units attributable to the first technology step equal zero. In similar fashion, the marginal cost of the first abatement unit of the second technology step equals TC_2 and MC of all subsequent abatement units attributable to the second technology step equal zero, and so on with each subsequent technology step.

of \$1.97 equals ((\$464,444 + \$49,823)/(91 lbs. + 623 lbs.))/365 days, or (91 lbs. / (91 lbs. + 623 lbs.)) * \$1.50 + (623 lbs. /(91 lbs. + 623 lbs.)) * \$2.04.

4. A Formal Comparison of Incremental and Average Control Costs

To compare IC with both AC_j and Weighted AC more formally, let $\bar{A}$ represent a source's total reduction needed, A_1 and A_2 represent reductions achieved for the source's technology steps 1 and 2, respectively, and $A = A_1 + A_2$. Assume $A \geq \bar{A}$, i.e., the source is capable of abating beyond its TMDL abatement allocation. Further, let TC_1 and TC_2 represent the annualized control costs associated with achieving A_1 and A_2, respectively, and $TC = TC_1 + TC_2$. There are two scenarios of particular interest.

<u>Scenario 1</u>

In the first scenario, we assume $A_1 \geq \bar{A}$, i.e., the source's step 1 technology is capable of generating a reduction level that exceeds its total reduction level required by the TMDL. In this case,

$$IC = \frac{TC_1}{\bar{A}} \geq AC_1 = \frac{TC_1}{A_1} \tag{1}$$

i.e., IC is at least as large as AC_1. Note from the information provided in Table 1, the three sources meeting the assumption for this scenario – WWTF #1, Stinky's Cheese, and Smelly's Cheese – all satisfy condition (1). In each case, $IC > AC_1$.

<u>Scenario 2</u>

In the second scenario, $A_1 < \bar{A}$ (but, as assumed earlier, $A \geq \bar{A}$), i.e., although the source's step 1 technology is incapable of generating a reduction level that exceeds its total reduction level required by the TMDL, steps 1 and 2 together are capable of generating such a reduction level. In this case, $IC = TC_2 / \left(\bar{A} - A_1\right)$, $AC_1 = TC_1 / A_1$, $AC_2 = TC_2 / A_2$, and Weighted $AC = TC/A$.

To begin, note that,

$$\frac{TC_2}{\bar{A} - A_1} \geq \frac{TC}{A} \Rightarrow \frac{TC_2}{TC} \geq \frac{\bar{A} - A_1}{A} \Rightarrow IC \geq \text{Weighted AC} \qquad (2)$$

i.e., IC is no less than Weighted AC when the reduction needed from the step 2 technology to ensure TMDL compliance as a percentage of the total reduction possible from technology steps 1 and 2 is less than the proportion of total control costs attributable to technology step 2. The comparison in (2) would be relevant for a source that has not yet implemented any control steps and is considering whether to implement both steps 1 and 2 to ensure TMDL compliance. Note that the inequality is more likely to hold the more efficient is the source's step 1 technology relative to its step 2 technology. From the information provided in Table 1, Bob's Farm satisfies condition (2). However, WWTF #2 does not, i.e., its Weighted AC exceeds its corresponding IC. A relatively high value of TC_2 / TC drives Bob's Farm's result, while a relatively high value of $\left(\bar{A} - A_1\right) / A$ (due to a relatively low value for A_1) drives WWTF #2's.

Next, note that

$$IC \geq AC_2 \qquad (3)$$

since $\left(TC_2 / \left(\bar{A} - A_1\right)\right) \geq \left(TC_2 / A_2\right)$. As envisioned in EPA [2004], this comparison is relevant for a source that had previously implemented step 1 technology and is now considering whether to implement step 2. In Table 1, both Bob's Farm and WWTF #2 satisfy condition (3). In the case of Bob's Farm, IC > AC_2 because $A > \bar{A}$, whereas in the case of WWTF #2, IC = AC_2 because $A = \bar{A}$. Lastly,

$$\frac{TC_2}{\bar{A} - A_1} \geq \frac{TC_1}{A_1} \Rightarrow \frac{TC_2}{TC_1} \geq \frac{\bar{A} - A_1}{A_1} \Rightarrow IC \geq AC_1 \tag{4}$$

i.e., IC is no less than AC_1 when the reduction needed from the step 2 technology to ensure TMDL compliance as a percentage of the total reduction possible from technology step 1 is less than the ratio of technology step 2's annualized control cost to step 1's. The comparison in (4) would be relevant for a source that has not yet implemented any control steps and is considering whether to implement solely step 1 technology to move toward TMDL compliance. Similar to the relationship between IC and Weighted AC, this inequality is more likely to hold the more efficient is the source's step 1 technology relative to its step 2 technology. From the information provided in Table 1, both Bob's Farm and WWTF #2 satisfy condition (4). Thus, while WWTF #2's step 1 technology is efficient enough to ensure IC > AC_1, it is not efficient enough to ensure IC > AC_2 or IC > Weighted AC.[15]

Conditions (1) – (4) may therefore be summarized as follows. In the case where technology step 1 is *capable* of meeting or exceeding the total reduction needed to comply with the source's TMDL abatement allocation (Scenario 1), IC exceeds its corresponding AC. In the case where technology step 1 is *incapable* of meeting the TMDL allocation (Scenario 2), IC may not exceed its corresponding AC. IC is more likely to exceed AC the more efficient is the source's step 1 technology relative to its subsequent technology steps.

[15] WWTF #2's AC_3 exceeds IC by a relatively large amount due to the relative inefficiency of its step 3 technology relative to its steps 1 and 2 technologies.

These results are important because given the discrete nature of abatement units, and thus the coincidence of AC and MC, AC represents a given source's WTP for abatement credits. In cases where IC exceeds(is exceed by) its corresponding AC, IC is thus perforce an over-(under-) estimation of WTP. As indicated by some of the costs calculated in Table 1, this over-(under-) estimation could potentially be quite large. Empirically speaking, control costs reported in EPA [2003, Exhibit 40] for an exhaustive list of actual WWTFs located in the Chesapeake Bay study area confirm that for at least some of those facilities IC is unlikely to exceed its corresponding AC.

5. Water Quality Trading with Discrete Abatement Units

Figure 2 depicts a stylized version of Scenario 2, as well as a discrete version of Figure 1 where the MC (cum "un-weighted" AC) curves similarly "cross" (explained in detail below). In this figure, a total of $\bar{A} = \bar{A}^1 + \bar{A}^2$ units of abatement across both sources is required by the regulatory authority (superscripts henceforth denote sources 1 and 2). We assume that $\bar{A} = \left(A_1^1 + A_2^1\right) = \left(A_1^2 + A_2^2\right)$, i.e., each source on its own has the capability of meeting the total abatement requirement using both of its technology steps. This assumption is necessary for admitting the possibility of corner solutions to the trading problem, and thus extends the range of possible trading scenarios under consideration.[16] Initial abatement allocations from the regulatory authority are labeled A_0^1 and A_0^2.

[INSERT FIGURE 2 HERE]

To begin, note in Figure 2 that Weighted AC^1 > Weighted AC^2. Thus, if the WTPs for sources 1 and 2 are reflected in their respective Weighted ACs rather than their respective AC_js (discussed below), trading results in a "move" from the initial allocation

[16] For example, in Figure 1 this would enable either MC_1 to lay everywhere above MC_2 or vice-versa, as long as the lower of the two curves spans the entire horizontal axis.

of $\left(A_0^1, A_0^2\right)$ to the "corner" allocation of $\left(0, \bar{A}\right)$, where source 1 abates nothing and source 2 abates the full amount. With respect to the Un-weighted Average Control Cost measures (i.e., AC_1^1, AC_2^1, AC_1^2, and AC_2^2), note that although source 2's successive average control costs for technology steps 1 and 2 (represented by AC_1^2 up to abatement level A_1^2 and AC_2^2 up to $\bar{A}$, respectively) are exceeded by source 1's corresponding average control costs (represented by AC_1^1 up to abatement level A_2^1 and AC_2^1 up to $\bar{A}$, respectively), AC_2^2 nevertheless exceeds AC_1^1. This is what is meant by the two source's Un-weighted AC curves crossing. It is a discrete analogue of the two continuous marginal abatement curves depicted in Figure 1, which, as mentioned in Section 2, is the classical depiction of the trading problem.[17]

To characterize a trading outcome involving sources 1 and 2 using solely the un-weighted average control cost measures, we refer to Figure 3, which is a redrawing of Figure 2 with pertinent rectangular areas demarcated.[18] For example, areas F + G and A + B + D represent source 2's total costs of control for technology steps 1 and 2,

[17] A second discrete analogue to the classical continuous trading problem – where AC_2^2 exceeds *both* AC_1^1 and AC_2^1 – is discussed in the Appendix. Note that the 'double-exceedance' analogue discussed in the Appendix is reflected in the potential trading relationship between WWTF #1 and WWTF #2 in Table 1, where the latter exhibits AC_1^1, AC_2^1, and AC_3^1 and the former exhibits AC_1^2 and AC_2^2, with $AC_1^2 < AC_1^1 < AC_2^1 < AC_3^1 < AC_2^2$. There are no sources in Table 1 with potential bilateral trading relationships that correspond to the 'single-exceedance' analogue depicted in Figure 3.

[18] Given that abatement is achieved in discrete units according to successive technology steps, it seems most likely that trading decisions will be based on the un-weighted rather than weighted average control costs.

respectively, while areas B and C + D + E + F + G similarly represent source 1's respective total costs of control.[19]

[INSERT FIGURE 3 HERE]

As mentioned in Section 1, to determine a possible trading outcome for sources 1 and 2 we must consider the gains from trade associated with a full sequence of possible sunk cost trading scenarios in any move away from initial allocation $\left(A_0^1, A_0^2\right)$ toward the corner solution $\left(0, \bar{A}\right)$.[20] The trading scenarios are aligned with the threshold abatement levels associated with each source's respective technology steps. For example, in Figure 3 the first scenario is represented by the move from initial allocation $\left(A_0^1, A_0^2\right)$ to allocation $\left(A_1^1, A_1^2\right)$, where source 2 reaches the threshold for its first technology step. The second scenario is represented by the move from allocation $\left(A_1^1, A_1^2\right)$ to $\left(A_2^1, A_2^2\right)$, where source 1 reaches the threshold for its first technology step. The final scenario is represented by the move from allocation $\left(A_2^1, A_2^2\right)$ to $\left(0, \bar{A}\right)$, where source 2 reaches the threshold for its second technology step.

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[19] If Figures 2 and 3 had instead been drawn such that $AC_2^2 < AC_j^1, j = 1, ..., m$, then similar to the result for the Weighted ACs discussed above, the corner allocation of $\left(0, \bar{A}\right)$ would naturally obtain through trading.

[20] The presumption that trading will move sources 1 and 2 toward allocation $\left(0, \bar{A}\right)$ as opposed to $\left(\bar{A}, 0\right)$ in Figure 3 is based on the comparison of Weighted AC curves in Figure 2 discussed above, as well as a comparison of the relative sizes of the sources' total abatement costs for technology steps 1 and 2 as depicted in the figure. Because source 1's total abatement cost (associated with achieving abatement level $\bar{A}$) of area A + D + F + G is depicted as being less than the corresponding total abatement cost for source 2 (area B + C + D + E + F + G + H) we presume that trading will achieve least total abatement cost at allocation $\left(0, \bar{A}\right)$. Obviously, we could have constructed Figure 3 such that least total cost occurs instead at allocation $\left(\bar{A}, 0\right)$, in which case our presumption would be that trading moves in that direction. In either case, we are able to make a direct comparison with the continuous abatement scenario depicted in Figure 1, which, as stated in Section 1, is the primary purpose of the present analysis.

This alignment of trading scenarios with the sources' respective technology steps reflects the 'lumpiness' of their abatement decisions. In turn, this creates the imputed sunk costs of abatement upon which the relative values of the abatement units themselves (i.e., the WTA and WTP measures described in Sections 2 – 4) are determined. In the end, the trading scenario associated with the largest gains from trade (i.e., WTP – WTA) is the most likely trading outcome.[21]

To determine the optimal trading scenario, we begin by assessing the gains from trade associated with the first of three possible scenarios (moving from the initial allocation $\left(A_0^1, A_0^2\right)$ to allocation $\left(A_1^1, A_1^2\right)$). Due to the discrete nature of abatement, source 2 incurs a total control cost of area F + G to be able to reach abatement level A_0^2 with its step 1 technology. The extra abatement beyond A_0^2 that source 2 obtains in step 1 (distance $A_1^2 - A_0^2$) therefore represents its available abatement credits; credits with an imputed (sunk) cost of area F.

Based on this imputed cost, source 2's WTA for these abatement credits is area $\theta_F F$, where $\theta_F \geq 0$ scales area F according to (i) the probability of source 2 finding a third party (other than source 1) with which to trade credits $A_1^2 - A_0^2$ and (ii) the price that source 2 ultimately obtains from the third party. For example, a relatively low θ_F could reflect the fact that source 2 has a very high probability of selling its credits to a third party, but at a

[21] This solution concept assumes that when two sources engage in a trading relationship they consider each of their mutually beneficial trading options at the outset. This is different than, say, sequential decision making, where the sources consider each trading option itself as a sequence of separate moves. For example, under sequential decision making the potential move from allocation $\left(A_0^1, A_0^2\right)$ to $\left(A_2^1, A_2^2\right)$ in Figure 3 is sequenced into two separate moves – first from $\left(A_0^1, A_0^2\right)$ to $\left(A_1^1, A_1^2\right)$ and then from $\left(A_1^1, A_1^2\right)$ to $\left(A_2^1, A_2^2\right)$. In this paper, we assume the sources will see no need to sequence a move like this in such a manner. In other words, the two sources engage in a one-shot rather than a repeated trading game.

very low price. A relatively high θ_F could mean that source 2 has a very low probability of selling its credits, but at a very high price. As a result, all we can say is that source 2's WTA for credits $A_1^2 - A_0^2$ is non-negative.[22]

Source 1, on the other hand, incurs an added imputed cost of area $\theta_{EF}(E + F)$ in moving from A_0^1 to A_1^1, where, similar to θ_F, $\theta_{EF} \geq 0$ scales area E + F according to the probability of source 1 finding a third party (other than source 2) with which to trade credits $A_0^1 - A_1^1$ and the price that source 1 ultimately obtains from the third party.[23] In other words, area $\theta_{EF}(E + F)$ represents source 1's WTP for source 2's credits of $A_1^2 - A_0^2$ = $A_0^1 - A_1^1$. It is the amount source 1 expects to obtain through the sale of its excess credits $A_0^1 - A_1^1$.

Sources 1 and 2 therefore have incentive to trade away from the initial allocation $\left(A_0^1, A_0^2\right)$ to the allocation represented by $\left(A_1^1, A_1^2\right)$ in Figure 3 if

$$\theta_{EF}(E + F) > \theta_F F \tag{5a}$$

Condition (5a) can be thought of as a necessary condition for sources 1 and 2 to agree to a move from $\left(A_0^1, A_0^2\right)$ to $\left(A_1^1, A_1^2\right)$. For future reference, if condition (5a) holds, we can define

[22] There are two things worthy of note here. First, θ_F is itself most likely a function of the number of market participants (i.e., available third parties) as well as expected transaction costs (as in Montero [1997]). Since the determination of θ_F is beyond the scope of our analysis, we assume without loss of generality that it is a constant term. Second, $\theta_F F$ can be considered as the discrete analogue to source 2's WTA amount c from source 1 in Figure 1 for an incremental move away from initial allocation (12.5, 12.5). Because marginal abatement costs are incurred incrementally in Figure 1, sunk costs are never encountered by the sources as they increase their abatement. Therefore, in assessing the potential of any given bilateral trade in a continuous framework the calculation of the seller's WTA for its abatement credits does not require an adjustment for the probability of selling to a third party.

[23] Note that prior to trading with source 2, source 1 had abatement credits of $\bar{A} - A_0^1$ valued at an imputed cost of area G + H. By moving from A_0^1 to A_1^1, source 1 effectively creates additional credits of $A_0^1 - A_1^1$, with an associated imputed value represented by area E + F.

$$\Omega_1 = \theta_{EF}(E + F) - \theta_F F > 0 \tag{5b}$$

as the gains from trade available to sources 1 and 2 associated with the move from $\left(A_0^1, A_0^2\right)$ to $\left(A_1^1, A_1^2\right)$. Also for future reference, note that the total cost of abatement for sources 1 and 2 under this possible trading scenario ends up being F + G (the cost to source 1) plus B + C + D + E + F + G + H – θ_{EF}(E + F) – θ_{GH}(G + H) (the cost to source 2), where θ_{GH} is the scaling factor for area G + H. Compared with the total cost associated with no trading (i.e., remaining at initial allocation $\left(A_0^1, A_0^2\right)$) of θ_FF + G + B + C + D + E + F + G + H – θ_{GH}(G + H), we see that, similar to the standard result for continuous abatement depicted in Figure 1, the total cost of abatement will necessarily decrease under the first trading scenario.[24]

Next, we consider a second possible trading scenario where sources 1 and 2 instead have incentive to trade away from allocation $\left(A_0^1, A_0^2\right)$ to the allocation represented by $\left(A_2^1, A_2^2\right)$. Following the same approach as for the first trading scenario discussed above, source 1's WTP for this move would be the cost savings associated with not having had to take its second technology step (i.e., area C + D + E + F + G + H) net of its expected revenue from the sale of abatement credits (area (1 – θ_{GH})(G + H)), where θ_{GH} is the scaling factor corresponding to imputed cost G + H. Source 2's overall WTA is comprised of its WTA for credits $A_1^2 - A_0^2$ (area θ_FF) plus the cost associated with implementing its step 2 technology (area A + B + D) net of its expected revenue from the

[24] The condition for total abatement cost to fall under the first trading scenario relative to no trading reduces to $\theta_F F < \theta_{EF}(E + F)$, which is necessary condition (5a). Alternatively stated, the reduction in total abatement cost for the two sources associated with moving from no trading to the first trading scenario is exactly equal to the gains from trade, condition (5b), or in the case of continuous abatement, area D in Figure 1. Similar types of comparisons can be made for the second and third trading scenarios (discussed below) versus the no-trade scenario.

sale of abatement credits $\bar{A} - A_2^2$ (area $\theta_{AB}(A + B)$), where θ_{AB} is the scaling factor corresponding to imputed cost A + B. Thus, the necessary condition for sources 1 and 2 to agree to a move from $\left(A_0^1, A_0^2\right)$ to $\left(A_2^1, A_2^2\right)$ can be written as

$$C + D + E + F + (1 - \theta_{GH})(G + H) > \theta_F F + D + (1 - \theta_{AB})(A + B). \tag{6a}$$

If condition (6a) holds, we can define

$$\Omega_2 = C + E + F + (1 - \theta_{GH})(G + H) - \theta_F F - (1 - \theta_{AB})(A + B) > 0 \tag{6b}$$

as the gains from trade available to sources 1 and 2 associated with the move from $\left(A_0^1, A_0^2\right)$ to $\left(A_2^1, A_2^2\right)$. In addition, we note that the sufficient condition for moving from $\left(A_0^1, A_0^2\right)$ to $\left(A_2^1, A_2^2\right)$, rather than to $\left(A_1^1, A_1^2\right)$ in the first trading scenario, is

$$\Omega_2 > \Omega_1. \tag{6c}$$

Thus, if conditions (6a) and (6c) both hold sources 1 and 2 will choose the second trading scenario over the first. Using the same logic as applied to the first two trading scenarios discussed above, the necessary condition for instead choosing the third trading scenario – moving from allocation $\left(A_0^1, A_0^2\right)$ all the way to $\left(0, \bar{A}\right)$ in Figure 3 – can be written as,

$$C + E + F + (1 - \theta_{GH})(G + H) > \theta_F F + A. \tag{7a}$$

If condition (7a) holds, we can define

$$\Omega_3 = C + E + F + (1 - \theta_{GH})(G + H) - \theta_F F - A > 0 \tag{7b}$$

as the gains from trade available to sources 1 and 2 associated with the move from $\left(A_0^1, A_0^2\right)$ to $\left(0, \bar{A}\right)$. In this case, the sufficient condition for making the move is

$$\Omega_3 > \Omega_2 \text{ and } \Omega_3 > \Omega_1 \tag{7c}$$

To sum up, if condition (7c) holds sources 1 and 2 will choose the third trading scenario and thus move from $\left(A_0^1, A_0^2\right)$ to $\left(0, \bar{A}\right)$. If condition (6c) holds but (7c) does not, sources 1 and 2 will instead choose the second trading scenario and thus move from $\left(A_0^1, A_0^2\right)$ to $\left(A_2^1, A_2^2\right)$. Finally, if neither condition (7c) nor (6c) hold sources 1 and 2 will choose the first trading scenario (and move from $\left(A_0^1, A_0^2\right)$ to $\left(A_1^1, A_1^2\right)$) if (5a) holds. Otherwise, the two sources will not choose to trade and thus remain at initial allocation $\left(A_0^1, A_0^2\right)$.

It is now easy to see why trading with discrete abatement units is inherently sensitive to the initial abatement allocation, unlike in the case of continuous abatement. Suppose the initial allocation in Figure 3 had been located at $\left(A_2^1, A_2^2\right)$ rather than $\left(A_0^1, A_0^2\right)$. In this case, the necessary *and* sufficient condition for moving from $\left(A_2^1, A_2^2\right)$ to $\left(0, \bar{A}\right)$ is

$$B > \theta_{AB}(A + B). \tag{8}$$

Because (8) is fundamentally different than (7c), and thus the necessary and sufficient conditions underlying the respective moves from $\left(A_0^1, A_0^2\right)$ and $\left(A_2^1, A_2^2\right)$ to $\left(0, \bar{A}\right)$ likewise diverge, we cannot conclude that if sources 1 and 2 have chosen to move to the corner allocation $\left(0, \bar{A}\right)$ from $\left(A_0^1, A_0^2\right)$ then they would also necessarily chose to move to $\left(0, \bar{A}\right)$ from $\left(A_2^1, A_2^2\right)$. In other words, the outcome in Figure 3 is indeed sensitive to the initial allocation of abatement responsibilities.

6. Conclusions

This paper has answered three questions related to the discrete nature of pollution abatement. The first question is, does incremental control cost necessarily exceed its corresponding average control cost, as presented in EPA (2004)? The answer is no. When its first technology step is incapable of achieving the source's target load, and the source has not previously implemented its first technology step, incremental control cost exceeds its corresponding average control cost only when the efficiency of its step 1 technology is large enough relative to its subsequent technology steps.

The second question – is a source's incremental control cost a better approximation of its willingness to pay for abatement credits than its average control cost? – again elicits the answer no. In the presence of discrete abatement units, average control cost is identically equal to marginal control cost. Since in general any source is capable of being a buyer or a seller of pollution reduction credits, the source's willingness to pay is ultimately equal to its marginal (and thus its average) control cost.

Lastly, how exactly does bilateral trading in the presence of discrete abatement differ from trading in the presence of continuous abatement? To this question we offer two answers. First, unlike with continuous abatement the trading outcome with discrete abatement units is determined by comparing the gains from trade associated with the full sequence of possible "sunk cost trading" scenarios. Second, the trading outcome with discrete abatement is generally dependent upon the initial allocation of abatement responsibilities. This, in turn, suggests that the numerical evidence provided in Montero [1997] relating the sensitivity of the trading outcome to the constancy of transaction costs in the presence of discrete abatement, is in fact more general than previously thought. Indeed, in the case where trading partners' average control cost curves "cross," the trading outcome is inherently sensitive to the initial allocation of abatement responsibilities.

Appendix

This appendix considers the case where, similar to Figure 3 in the text, the Un-weighted abatement cost curves for sources 1 and 2 cross. However, while the cost curve for source 2's first technology step lies everywhere beneath source 1's cost curves for both its first and second technology steps (as in Figure 3), the cost curve for source 2's second technology step lays everywhere above both of source 1's cost curves. This case is depicted in Figure A1.

[INSERT FIGURE A1 HERE]

Following the same solution procedure as used Section 5, we first note that the necessary condition for, and the gains from trade associated with, a move from initial allocation $\left(A_0^1, A_0^2\right)$ to allocation $\left(A_1^1, A_1^2\right)$ in Figure A1 (i.e., the first trading scenario) are identical to conditions (5a) and (5b), respectively. With respect to the second trading scenario, conditions (6a) and (6b) become, respectively,

$$D + E + F + (1 - \theta_{GH})(G + H) > \theta_F F + C + D + (1 - \theta_{AB})(A + B) \qquad (6a')$$

and

$$\Omega_2 = E + F + (1 - \theta_{GH})(G + H) - \theta_F F - C - (1 - \theta_{AB})(A + B) > 0. \qquad (6b')$$

Based on conditions (5b) and (6b′), (6c) is also the relevant sufficient condition for the second trading scenario in Figure A1.

With respect to the third trading scenario, conditions (7a) and (7b) become, respectively,

$$E + F + (1 - \theta_{GH})(G + H) > \theta_F F + A + C. \qquad (7a')$$

and

$$\Omega_3 = E + F + (1 - \theta_{GH})(G + H) - \theta_F F - A - C > 0 \qquad (7b')$$

Based on (5b), (6b′), and (7b′), condition (7c) is also the relevant sufficient condition for the third trading scenario in Figure A1.

As in the text, we now suppose the initial allocation in Figure A1 had been located at $\left(A_2^1, A_2^2\right)$ rather than $\left(A_0^1, A_0^2\right)$. In this case, the necessary and sufficient condition for moving from $\left(A_2^1, A_2^2\right)$ to $\left(0, \bar{A}\right)$ would still be (8). Thus, as in the case of Figure 3, the outcome in Figure A1 is indeed sensitive to the initial allocation of abatement responsibilities.

References

Atkinson, S.E. and Morton, B.J. (2004). Determining the cost-effective size of an emission trading region for achieving an ambient standard. Resource and Energy Economics, 26(3), 295-315.

Atkinson, S.E. and Tietenberg, T. (2001). Market failure in incentive-based regulation: The case of emissions trading. In Tietenberg, T. (Ed.) Emissions trading programs, volume 2, theory and design. Aldershot, U.K.: Ashgate.

Atkinson, S.E. and Tietenberg, T. (1991). Market failure in incentive-based regulation: The case of emissions trading. Journal of Environmental Economics and Management, 21, 17-31.

Baldursson, F.M. and von der Fehr, N-H. M. (2004). Price volatility and risk exposure: On market-based environmental policy instruments. Journal of Environmental Economics and Management, 48(1), 682-704.

Becker, N., Baron, M., and Schechter, M. (1993). Economic instruments for emission abatement under appreciable technological indivisibilities. Environmental and Resource Economics 3(3), 263-284.

Bernstein, M.A., Farrell, A.E., and Winebrake, J.J. (1994). The impact of restricting the SO_2 allowance market. Energy Policy, 22, 748-754.

Bohi, D.R. and Burtraw, D. (1992). Utility investment behavior and the emission trading market. Resource and Energy Economics, 14, 129-153.

Cason, T.N., Gangadharan, L., and Duke, C. (2003). Market power in tradable emission markets: A laboratory testbed for emission trading in Port Phillip Bay, Victoria. Ecological Economics, 46(3), 469-491.

Chao, H-P and Wilson, R. (1993). Option value of emission allowances. Journal of Regulatory Economics, 5, 233-249.

Coggins, J.S. and Smith, V.H. (1993). Some welfare effects of emission allowance trading in a twice-regulated industry. Journal of Environmental Economics and Management, 25, 275-297.

Cronshaw, M.B. and Kruse, J.B. (1996). Regulated firms in pollution permit markets with banking. Journal of Regulatory Economics, 9, 79-89.

Environomics (1999) A summary of U.S. effluent trading and offset projects. Report prepared for the U.S. Environmental Protection Agency, Office of Water Quality.

Farrow, R.S., M.T. Schultz, P. Celikkol, and G.L. Van Houtven (2005). Pollution trading in water quality limited areas: Use of benefits assessment and cost-effective trading ratios. Land Economics, 81(2), 191-205.

Fullerton, D., McDermott, S.P., and Caulkins, J.P. (1997). Sulfur dioxide compliance of a regulated utility. Journal of Environmental Economics and Management, 34(1), 32-53.

Germain, M., Van Steenberghe, V., and Magnus, A. (2004). Optimal policy with tradable and bankable pollution permits: Taking the market microstructure into account. Journal of Public Economic Theory, 6(5), 737-757.

Hahn, R.W. (1989). Economic prescriptions for environmental problems: How the patient followed the doctor's orders. Journal of Economic Perspectives, 3, 95-114.

Hahn, R.W. (1984). Market Power and transferable property rights. Quarterly Journal of Economics, 99, 753-765.

Hahn, R.W. and Hester, G.L. (1989a). Marketable permits: Lessons for theory and practice. Ecology Law Quarterly, 16, 361-406.

Hahn, R.W. and Hester, G.L. (1989b). Where did all the markets go? An analysis of EPA's emissions trading program. Yale Journal on Regulation, 6, 109-153.

Hahn, R.W. and May, C. (1994). The behavior of the allowance market: Theory and evidence. Electricity Journal, 7, 28-37.

Halkos, G.E. (1994). Optimal abatement of sulphur emissions in Europe. Environmental and Resource Economics 4(2), 127-150.

Hung, M-F. and Shaw, D. (2005). A trading-ratio system for trading water pollution discharge permits. Journal of Environmental Economics and Management, 49(1), 83-102.

Joskow, P.L. and Schmalensee, R. (1986) Incentive regulation for electric utilities. Yale Journal of Regulation, 4, 1-49.

Keeler, A.G. (1991) Noncompliant firms in transferable discharge permit markets: Some extensions. Journal of Environmental Economics and Management, 21, 180-189.

King, D.M. (2005) Crunch time for water quality trading. Choices, 20(1), 71-75.

Konishi, H. (2005). Intergovernmental versus intersource emissions trading when firms are noncompliant. Journal of Environmental Economics and Management, 49(2), 235-261.

Kolstad, C.D. (2000). Environmental economics. New York: Oxford University Press.

Lund, J.R. (1993). Transaction risk versus transaction costs in water transfers. Water Resources Research, 29, 3103-3107.

Magat, W.A., Krupnick, A.J., and Harrington, W. (1986). Rules in the making. Washington, DC: Resources for the Future.

Malik, A.S., D. Letson, and S.R. Crutchfield (1993). Point/nonpoint source trading of pollution abatement: Choosing the right trading ratio. American Journal of Agricultural Economics, 75, 959-967.

Misiolek, W.S. and Elder, H.W. (1989) Exclusionary manipulation of markets for pollution rights. Journal of Environmental Economics and Management, 16, 156-166.

Montero, J-P. (1997). Marketable pollution permits with uncertainty and transaction costs. Resource and Energy Economics, 20(1), 27-50.

Nemetz, P.N. and Drechsler, H.D. (1979). Least cost solutions to the problem of effluent abatement in urban systems. Water Resources Bulletin 15(5), 1374-1384.

O'Neil, W.B. (1983). The regulation of water pollution permit trading under conditions of varying streamflow and temperature. In Joeres, E.F. and David, M.H. (Eds.) Buying a better environment: Cost-effective regulation through permit trading. Madison, WI: University of Wisconsin Press.

Rousseau, S. and Proost, S. (2005). Comparing environmental policy instruments in the presence of imperfect compliance – a case study. Environmental and Resource Economics 32(3), 337-365.

Rubin, J.D. (2001). A model of intertemporal emission trading, banking, and borrowing. In Tietenberg, T. (Ed.) Emissions trading programs, volume 2, trading and design. Aldershot, U.K.: Ashgate.

Shortle, J.S. (1987). Allocative implications of comparisons between the marginal costs of point and nonpoint source pollution abatement. Northeast Jouranl of Agricultural and Resource Economics, 16, 17-23.

Shortle, J.S. (1990). The allocative efficiency implications of water pollution abatement cost comparisons. Water Resources Research, 26, 793-797.

Shortle, J.S. and R.D. Horan (2005). When two wrongs make a right: Second best point-nonpoint trading ratios. American Journal of Agricultural Economics, 87(2), 340-352.

Stavins, R. (1995). Transaction costs and tradable permits. Journal of Environmental Economics and Management, 29, 133-148.

Tietenberg, T. (2006). Environmental and natural resource economics, seventh edition. Boston: Pearson Education, Inc.

United States Environmental Protection Agency. (2004, November). Water quality trading assessment handbook. EPA 841-B-04-001. Washington DC: Author. Available online at http://www.epa.gov/owow/watershed/trading/handbook/index.html.

United States Environmental Protection Agency. (2003, September). Economic analysis of nutrient and sediment reduction actions to restore Chesapeake Bay water quality. Region III Report from the Chesapeake Bay Program Office. Annapolis, Maryland: Author.

United States General Accounting Office (GAO). (1994). Air pollution: Allowance trading offers an opportunity to reduce emissions at less cost. GAO/RCED-95-30. Washington, DC: Author.

Winebrake, J.J., Farrell, A.E., and Bernstein, M.A. (1995). The clean air act's sulfur dioxide emissions market: Estimating the costs of regulatory and legislative intervention. Resource and Energy Economics, 17, 239-260.

Wen, S-Y., Penm, J.H.W., and Terrell, R.D. (2005). A dynamic investigation of permits auctions with industrial restructuring. Empirical Economics Letters, 4(1), 25-35.

Figure 1. Water Quality Trading in the Presence of Continuous Abatement Units.

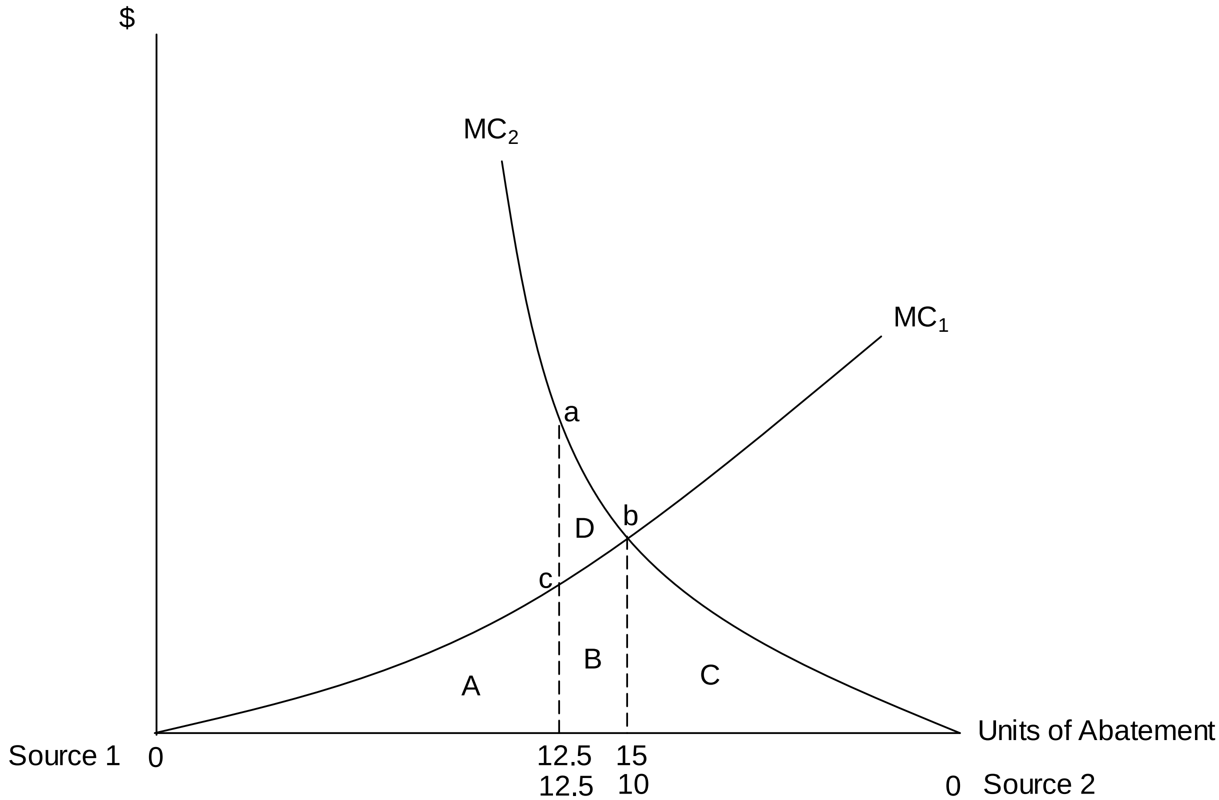

Figure 2. Water Quality Trading in the Presence of Discrete Abatement Units.

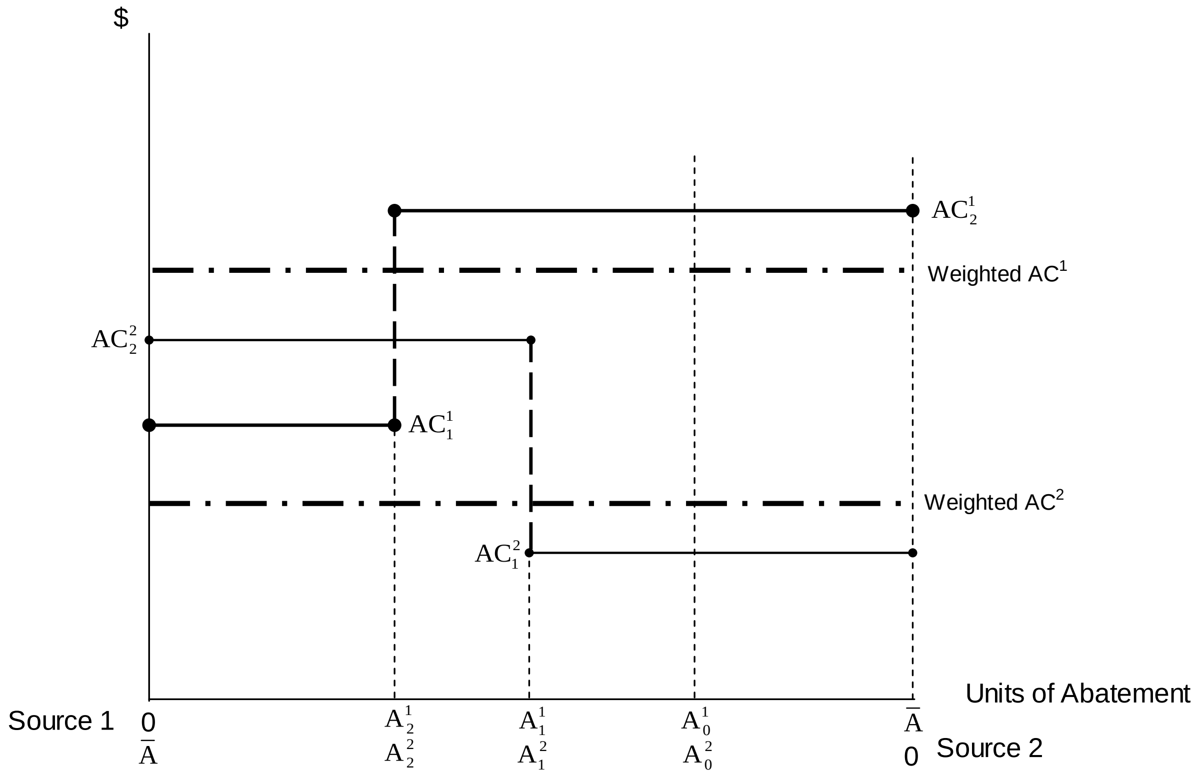

Figure 3. Likely Trading Outcome in the Presence of Discrete Abatement Units.

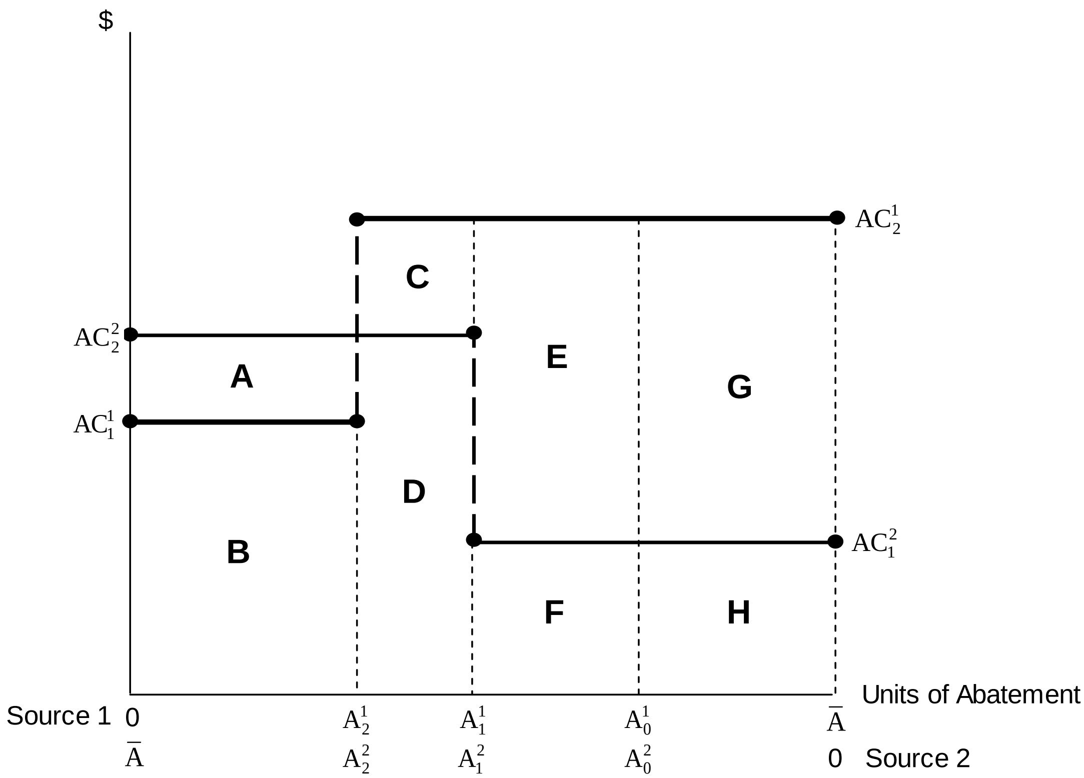

Figure A1. Another Example of Discrete Abatement.

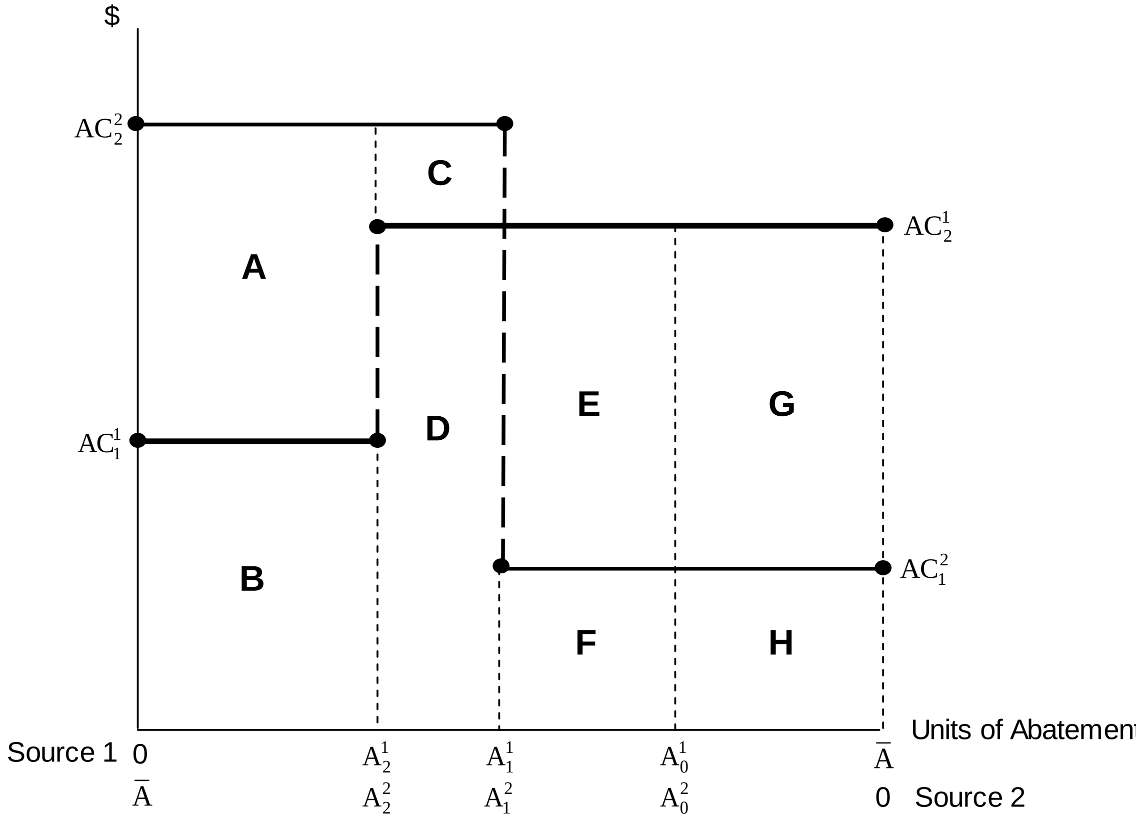

Table 1. Hypothetical Cost of Control and Control Effectiveness Data.*

Source	Current Load	Target Load	Reduction Needed	Incremental Reduction Achieved	Cumulative Reduction Achieved	Reduction Needed for Compliance	Credits	TC	IC	AC	Weight. AC
Bob's Farm	873	527	346								
Step 1				91	91	255	0	49,823	---	1.50	---
Step 2				623	714	0	368	464,444	4.99	2.04	1.97
WWTF #1	917	633	284								
Step 1				662	662	0	378	2,074,237	20.01	8.58	---
Step 2				107	769	0	485	5,222,364	---	133.72	26.00
Stinky's Cheese	698	410	288	506	506	0	218	6,308,251	60.01	34.16	34.16
WWTF #2	72	25	47								
Step 1				10	10	37	0	56,032	---	15.35	---
Step 2				37	47	0	0	219,022	16.22	16.22	---
Step 3				20	67	0	20	339,450	---	46.50	25.13
Smelly's Cheese	274	166	108	163	163	0	55	590,906	14.99	9.93	9.93

*The actual Excel spreadsheet in electronic form for this figure is available upon request from the author. All physical measurements (e.g., Current Load, Target Load, etc.) are in lbs. per day. TC is measured in dollars, IC is in dollars per reduction needed for compliance, AC is in dollars per incremental reduction achieved, and Weighted AC is in dollars per weighted average of incremental reductions achieved.