Simulated Trading for Maryland's Nitrogen Loadings in the Chesapeake Bay

James C. Hanson and K.E. McConnell

We investigate nutrient trading for point and non-point sources for the Bay Restoration Fund in Maryland. We demonstrate how to use the proceeds from the tax revenue to mimic a market by trading high-cost upgrades of sewage treatment plants for low-cost winter cover crops. Under an optimistic assumption about costs for non-point sources and naïve assumptions about the lag from planting cover crops to changes in nitrogen load, we calculate that 100 percent of abatement could be achieved at 56 percent of total costs, while in a pessimistic scenario, 100 percent of abatement could be could be achieved at 83 percent of total costs.

Key Words: Chesapeake Bay, cover crops, nitrogen abatement, nutrient trading, sewage treatment plants, trading ratios, water pollution

Recent initiatives in air pollution policy have emphasized the efficiency of incentive-based mechanisms for reducing pollution. The best example is the sulfur dioxide (SO_2) trading program, although there are a number of other incentive-based programs in the Clean Air Act and its amendments, including pollution permit trading programs for mercury and nitrous oxides.[1]

The success of incentive-based mechanisms in reducing air pollution has led to their use in water pollution policy, where progress has been slower. The most familiar of these mechanisms is water pollution permit markets, which have considerable support from the U.S. Environmental Protection Agency and various state government agencies.[2] Breetz et al. (2004) list over 70 such programs in various stages of development [see King and Kuch (2003) and Breetz et al. (2004) for summary data on these programs]. Unfortunately, there have been only a limited number of voluntary trades to date, suggesting that there are barriers to be overcome if nutrient trading is going to be a viable water quality policy.

The requirements for water quality pollution trading are similar to those for air pollution permit trading. The characteristics of buyers and sellers of permits must be determined. Some of the buyers or sellers must be polluters who have pollution caps on an individual or enterprise basis. The baseline levels of pollution emission of all sellers must be known. Finally, there must be active monitoring and enforcement. It is essential to have a public representative, such as a governmental agency, representing the public interest to ensure that the contract terms of the trade are reasonable and are met.

We deal with water pollution from two sources: point and non-point. Measurement of emissions is feasible for point sources, such as a publicly owned treatment plant, but a significant challenge for non-point sources. The uncertainty that characterizes non-point sources is all the greater because weather plays a major role in these emissions. Because the link between conservation practices and nutrient abatement is uncertain, trading such practices for point source abatement is a gamble. Moreover, trading conservation practices instead of abatement hinders the ability of farms to seek more effective ways of nutrient abatement.

Much of the discussion of non-point source trading revolves around the notion of the trading ratio—the quantity of non-point source abatement

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[1] See Gayer and Horowitz (2005) for a comprehensive study of incentive-based pollution control policies.

[2] The idea of nutrient trading for the Chesapeake Bay has circulated for some years. See the general ideas suggested by the Chesapeake Bay Program in its report "Chesapeake Bay Program Nutrient Trading Fundamental Principles and Guidelines" at http://www.chesapeakebay.net/trading.htm.

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traded for point source abatement. The popular argument is that the trading ratio should be greater than one, to account for the greater uncertainty of non-point source abatement (King and Kuch 2003). This conclusion is problematic, and stumbles on the distinction between abatement uncertainty and emissions uncertainty. Shortle (1987) has observed that while increases in the abatement of non-point sources at the expense of point sources may increase the uncertainty of abatement, they may reduce the uncertainty of emissions. Malik, Letson, and Crutchfield (1993) reach a more ambiguous conclusion, based on a more complex model.[3] Because ultimately the public is most concerned about the damages caused by emissions (and is willing to incur costs to reduce it), it makes sense in policy decisions to focus on emissions, rather than abatement. Toward that end, Shortle (1987) identifies a trading ratio of less than one as a tool for encouraging non-point source abatement and reducing the uncertainty of loadings. In a general model, Hennessy and Feng (2008) demonstrate the force of arguments for a trading ratio that favors non-point sources.

Although the idea of water pollution permit trading is old and the debate over its feasibility considerable [see King and Kuch (2003) for references], there is very little empirical evidence on the potential gains from trade. It is obvious that the presence of heterogeneous abatement costs presents an opportunity to gain from trade. We contribute to the literature by providing evidence of the potential abatement costs for a modest trading system in Maryland. We also discuss a variety of agronomic and political forces that may make true markets for pollution permits difficult to establish.

We investigate nutrient trading for point and non-point sources in the specific policy presented by the Bay Restoration Fund (Maryland Senate Bill 320), widely known as the Flush Tax, in Maryland. The Flush Tax is expected to abate nitrogen emissions in the state by 7.5 million pounds, primarily from improvements in sewage treatment plants. To put that reduction in perspective, there was a flow of 56.7 million pounds of nitrogen into the Bay from all Maryland sources such as agriculture, urban non-point, and sewage treatment plants in 2002. The 2020 strategy goals require a reduction of 20 million pounds, to 37.25 million pounds. The 7.5 million pound reduction to be achieved by enacting the Flush Tax will accomplish one-third of the overall strategy reduction (Summers 2005).

We demonstrate the workings of an "administered" trading system by maximizing abatement of nitrogen from Maryland publicly owned (sewage) treatment works (POTWs) and agricultural non-point sources subject to the restriction that costs not exceed the revenues generated by the Flush Tax. This administered trading system mimics a market for pollution permits by swapping low cost upgrades of POTWs and low cost winter cover crops for higher cost upgrades of POTWs. Trading exploits heterogeneous abatement costs for treatment plants and for agriculture, creating substantial cost savings that could be used for increased abatement of nutrients. Under an optimistic assumption about abatement costs for non-point sources, we calculate that 100 percent of abatement could be achieved at 56 percent of total costs, while in a pessimistic scenario, 100 percent of abatement could be achieved at 83 percent of total costs. We also explore the role of uncertainty in determining the appropriate trading ratio between point and non-point sources of pollution to maximize improvements in water quality.

We label the scheme "administered" because it relies on observable abatement costs in the case of POTWs and on revealed costs for farms with cover crops. Consequently, such a scheme could presumably be managed by a government agency. Cost savings from a more sophisticated trading system, with a true market for loadings permits, would lead to greater cost savings because a true market would permit firms to seek out cost savings that would not be observable by government agencies. However, trading loadings permits has a number of significant barriers, including the chief problem of measuring loadings from non-point sources.

While it is encouraging to identify the gains that would result from exploiting differences in abatement costs, the barriers to effective trading are extensive. We identify institutional and technical barriers that might prevent taking advantage of these opportunities. We also examine the change

[3] See also Horan (2001), who argues for political forces as leading to higher trading ratios.

in phosphorus loadings as a byproduct of nitrogen-based administrated trading decisions.

The Maryland Flush Tax Legislation[4]

In May 2004, then Maryland Governor Robert Ehrlich signed the "Flush Tax" into law effective January 1, 2005. The Flush Tax, which has the objective of helping Maryland meet its obligation to reduce nutrient flow to the Bay, requires the owner or resident of each dwelling unit to pay an additional $7.50 per quarter on its water bill. An annual fee of $30 is levied on homeowners with septic systems. The fund has three purposes:

- to upgrade sewage treatment plants from biological nutrient reduction (BNR) to enhanced nutrient reduction (ENR), which are both methods that reduce nutrients from sewage,
- to expand the use of winter cover crops,
- to fund the improvement of homeowner septic systems that are located in areas designated as critical in the Bay tributary strategy.

The Flush Tax will raise approximately $60 million annually from users of POTWs. Another $12 million will be raised annually from the estimated 420,000 private users of septic systems. Of the funds raised from septic system operators, 60 percent will go to refitting failing septic systems in critical areas of the state, and the remaining 40 percent to funding agricultural cover crops. There are concerns, however. The current levels of funding will cover only about 54 of the 66 POTWs; an additional $161–$411 million will be needed to cover the remainder (Maryland Tributary Teams 2006). In addition, the open commitment to fund the full costs of upgrades creates an adverse incentive for the plants to design a more expensive version of enhanced nutrient management, perhaps exacerbating these funding shortages.

The vast majority of the funds will be used to upgrade sewage treatment plants. Specifically, funds will upgrade 66 major sewage treatment plants from biological nutrient reduction (BNR) to state-of-the-art enhanced nutrient reduction (ENR). With BNR, treated sewage has 8 mg/l of total nitrogen. With ENR, total nitrogen is lowered to 4 mg/l and phosphorus is reduced to 0.3 mg/l. Sewage treatment plants are designated as major if they have at least 500,000 gallons of daily flow. All major POTWs are required to upgrade. They account for 95 percent of the wastewater flow from Maryland into the Bay.

An essential element of any trading system is a set of individual caps for some polluters. As part of the Flush Tax legislation, nitrogen and phosphorus caps (pounds per year) have been established for each individual POTW, based on their daily discharges. The POTWs have two different estimates of flow for 2020 (projected flow and design flow), as shown in their County Water and Sewer Plan. Both estimates were approved by the Maryland Department of the Environment in April 2003. Design flow is larger than projected flow because it takes into account higher population growth projections. The caps for nitrogen are equal to the product of the design flow and the ENR for nitrogen.

The implication of these two flows is that, in the short run, a POTW that upgrades to ENR will be operating under its nitrogen and phosphorus caps. But, as population grows in that municipality, *reflecting* the higher design flow, the POTW will increase its emissions of nitrogen and phosphorus until it meets its caps. At that point, it would be allowed to trade with another POTW that is operating under its caps or purchase an offset to its emissions.

The aggregate nitrogen cap for Maryland is the sum of the 66 POTWs in the state, or 9,145,817 pounds per year of nitrogen (Table 1). Sewage treatment plants in Maryland are dominated by the Blue Plains sewage treatment plant (the Maryland portion not associated with Washington, D.C.) and the Back River sewage treatment plant (Baltimore City), which serve the two major population centers of the state. Table 1 shows the nitrogen released under BNR and ENR technologies and the costs of abatement for ENR for the two large POTWs and the remaining 64 smaller POTWs. The two large POTWs are responsible for 48 percent of the nitrogen released into the Chesapeake Bay from controllable Maryland sources, and the cost of converting them from BNR to ENR will absorb 64 percent of the appropriated Flush Tax funds.

[4] For a good summary of Maryland's point source strategy to upgrade wastewater treatment plants to state-of-the-art enhanced nutrient removal (ENR), see Maryland Tributary Teams (2006). The description of the Flush Tax in this section is taken from that document.

Table 1. Annual Loadings of Nitrogen, 2000, Nitrogen Cap Projected for 2020, and the Capital Costs of Upgrading

	Annual Emissions of Nitrogen (lbs/year)		
	2000 Total Nitrogen Load	ENR N Cap	Capital Costs for ENR
Blue Plains	3,367,631	2,066,108	$377,200,000
Back River	4,529,473	2,192,803	$100,000,000
64 smaller POTWs	8,681,877	4,886,906	$263,742,760
TOTAL	16,578,981	9,145,817	$740,942,760

Source: Maryland Tributary Teams (2006) and Levelev (2004).

Note: Nitrogen cap projection based on enhanced nutrient reduction (ENR) with design flow.

Administered Nutrient Trading Among POTWs and Cover Crops

We explore administered nutrient trading, which is a more expansive version of nutrient trading than that allowed in the Flush Tax legislation but more restrictive than would emerge under a market for nutrient emission permits. Administrative trading is motivated solely by differences in the average abatement costs from different sources. This program optimizes in the same sense that markets optimize—by allocating abatement to the least-cost alternatives. We begin by grouping the POTWs by trading areas (Table 2). We consider two levels of trading: watersheds and statewide, but a similar process could occur with tributaries. Blue Plains and Back River were excluded from the trading scheme because they were too large to trade with the smaller POTWs. They were assumed to have been upgraded from BNR to ENR. Any gains from trading will be seen with the remaining 64 POTWs.

We compute the marginal abatement curves for nitrogen for the individual regions and for Maryland as a whole by using abatement from the cheapest source first, whether POTWs or cover crops. Within a given trading region, we minimize the cost of meeting the aggregate regional cap based on the region's marginal abatement schedule. The approach optimizes the same way trading in a market optimizes—the cheapest sources go first. However, this type of trading is not market-based, but administered by the government. Efficiencies can be achieved across enterprises, but not within enterprises, reflecting cost savings from heterogeneity but not from incentives. The greatest potential gains in cost savings, whether in a cap-and-trade program or in a market economy, come from the ability of a firm to seek new and cheaper ways of meeting goals. Frequently these cost savings involve responses that were not apparent when there was no opportunity to save money. For example, the costs of SO_2 were considerably overestimated prior to the inception of the SO_2 trading program.[5] While the static savings from trading that we uncover are almost certainly less than would be revealed under a system of full property rights for pollution permits, understanding the workings of the administered trading system would be essential to the implementation of a broader system.

The costs of abating nitrogen from sewage treatment plants are based on the annualized capital costs. For each sewage treatment plant, we have the total capital cost of upgrading from BNR to ENR. Under the assumption that the plant operates at projected flow, we calculate the annual reduction in nitrogen as a consequence of the upgrade. The average annual abatement costs for the ith plant are

$$(1) \qquad aac_{pi} = ACC_i \,/\, [q_i * (k_{bnr} - k_{enr})],$$

where AAC_i is the annualized capital costs,[6] q_i is projected flow of wastewater, and k_{enr} and k_{bnr} are the nitrogen concentrations for BNR and ENR (8 mg/l and 4 mg/l, respectively). Note that this

[5] See for example Schmalensee et al. (1998).

[6] Annualized under the assumption that the improvement will last 20 years, with an interest rate of 5 percent.

Table 2. Sewage Treatment Plants (POTWs) in Watersheds, and Tributaries

Maryland State: 64 POTWs (excluding Blue Plains and Back River)	
Watershed	Tributary
Eastern Shore watershed (19 POTWs)	Choptank tributary (3 POTWs)
	Lower Eastern Shore tributary (9 POTWs)
	Upper Eastern Shore tributary (7 POTWs)
Potomac River watershed (23 POTWs)	Lower Potomac River tributary (5 POTWs)
	Middle Potomac River tributary (4 POTWs)
	Upper Potomac River tributary (14 POTWs)
Western Shore watershed (15 POTWs)	Lower Western Shore tributary (6 POTWs)
	Upper Western Shore tributary (5 POTWs)
	Patapsco/Back River tributary (4 POTWs)
Patuxent River watershed (7 POTWs)	Patuxent River tributary (7 POTWs)

abatement cost equation assumes that the baseline for all firms is BNR, a condition that is currently not true.[7] This calculation of costs omits variable costs, which are believed to be small but not zero. We have written the cost equation for abatement from sewage treatment plants assuming that there is no randomness in the nitrogen emissions. There is typically randomness because of weather or surges in loads, but these effects are small in comparison with randomness from non-point sources.

The costs for farms of abating nitrogen using cover crops are based on the payment made to induce farms to adopt cover crops, as well as the efficiency of the cover crops in abating nitrogen. We estimate the costs by considering the efficiency of cover crops to reduce nitrogen emissions, conditional on the type of cultivation practiced. That is, a nitrogen cover crop will induce more abatement on high-tillage corn than on low-tillage corn, because the high-tillage crop begins with higher emissions. Given the institutional structure of paying a single price to all farmers enrolled, the abatement costs are calculated as follows:

(2) $$aac_{ni} = AP / \ (k_{ef} * e_{i0}),$$

where aac_{ni} is the average abatement cost for the ith non-point enterprise, AP is the adoption price per acre paid to farms to plant cover crops, k_{ef} is the proportional efficiency of cover crops in reducing nitrogen, and e_{i0} is the baseline level of emissions per acre for the ith enterprise. The baseline level of emissions is idiosyncratic, depending on such factors as the cultivation methods, previous crops grown, soil type, slope, and weather. In particular, the baseline will be lower for farms that have pursued environmentally sound cultivation techniques. As equation (2) indicates, the abatement costs will be higher for farms that have lower baseline levels of nitrogen loadings, and those farms as a consequence will be less likely to enroll in cover crop programs when the programs are managed on the basis of minimizing abatement costs. In Maryland the adoption price has been determined by political forces, the state of the budget, and the immediacy of the environmental issues.

Heterogeneity of abatement costs from cover crops stems from variation in the efficiency parameter k_{ef} and the baseline level of nitrogen loss, e_{i0}. Early planting of cover crops yields efficiencies of 30 percent. Late planting (after October 1) reduces efficiency to 15 percent. Cover crops are more cost-effective when they follow a high-tillage crop, the baseline. For example, an acre of high-tillage corn may lose 20 pounds of nitrogen to groundwater. With the application of an early

[7] Currently over half of the POTWs are not even at BNR. Some of these upgrades are costly, especially for small communities. There are good opportunities for cost-saving arbitrage for these upgrades too.

planted cover crop (30 percent efficiency), the reduction in nitrogen lost is 6 pounds. In comparison, a conservation tillage crop of corn may lose only 15 pounds of nitrogen. Early planted cover crops (30 percent efficiency) reduce nitrogen losses by only 4.5 pounds per acre.[8]

The current approach to allocating funds for adoption of cover crops and other green practices fails to achieve least cost for nitrogen abatement. However, if farms were to adopt cover crops based on the costs of abating nitrogen, then offering a fixed price for enrollment would generate a least-cost approach to allocating funds to this practice. When farms have heterogeneous costs of adoption, as they almost certainly do, then we expect that *AP* would cover the adoption costs of the highest cost abater, giving the more efficient abaters surplus from the constant price. In Figure 1, "MAC" represents the marginal abatement cost from planting cover crops. It is created by ranking the farms from lowest to highest in terms of the costs of abating nitrogen with cover crops. (In practice this curve would be a step function where the horizontal length of the step would be the farm's contribution to nitrogen reduction.) The marginal farm is just induced to plant cover crops at the price AP, bringing the quantity of abatement to N. Other farms incur costs below AP. The net gain to farmers from this method of subsidizing cover crops and abating nitrogen is the area ONM.

In the practice of subsidizing cover crops in Maryland and other states, however, farms sign up for cover crops based on the cost of cultivating the cover crops, not the cost of nitrogen abatement. For example, two farms that are identical except that one has a baseline of high-till corn and the other low-till corn would be equally eligible, though the high-till corn farm would have the lower cost in nitrogen reduction. Hence, the actual practice of allocating funds to cover crops does not yield a least-cost approach to abatement. Hence the application of this incentive-based mechanism requires that farms be ranked in terms of the reductions in nitrogen loadings. Information for such a ranking is inherent in the data sources we use to calculate baseline nitrogen loadings by farm.

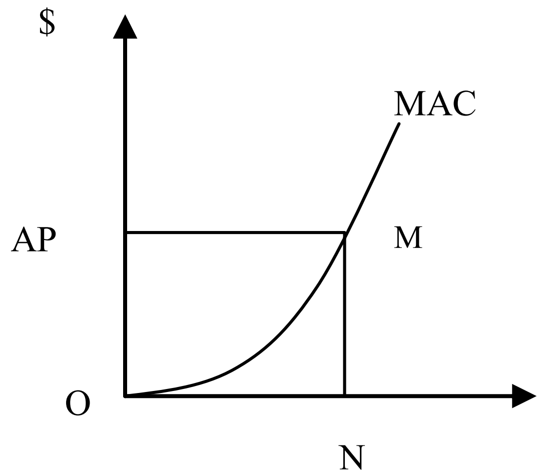

Figure 1. Nitrogen Abatement with Cover Crops

Our method of calculating costs in equation (2) does a reasonable job of locating the most efficient non-point sources first. That is, without establishing additional institutions, we can combine information on the cost of inducing the cover crop with agronomic information on the effectiveness of the cover crop to provide an understanding of how to allocate the Flush Tax funds. Because we account for differences in baselines and differences in the location of farms, we have plausible estimates of the cost of abating nitrogen. As with point sources, greater savings can be achieved with incentive-based mechanisms for allocating funds.

As we explain below, there are some substantial differences in how long it takes nitrogen to reach the Bay from non-point sources compared to point sources. In particular, the lag for point sources may be quite substantial, so that current abatement of non-point sources may take anywhere from weeks to years to have an impact on ambient water quality in the Bay. Hence one must be cautious in interpreting the results.

Gains from Trading

The fundamentals of trading are presented in Figure 2, which gives the incremental abatement cost for POTWs and cover crops on the left axis, with

[8] Cover crop acreages and nitrogen loading data were taken from the Chesapeake Bay Program Watershed Model Output Data, Detailed Loads and Land Use Acreage, Edge Stream Load Land (see http://www.chesapeakebay.net/pubs/waterqualitycriteria/Loads_Landuse_Detail.xls for details).

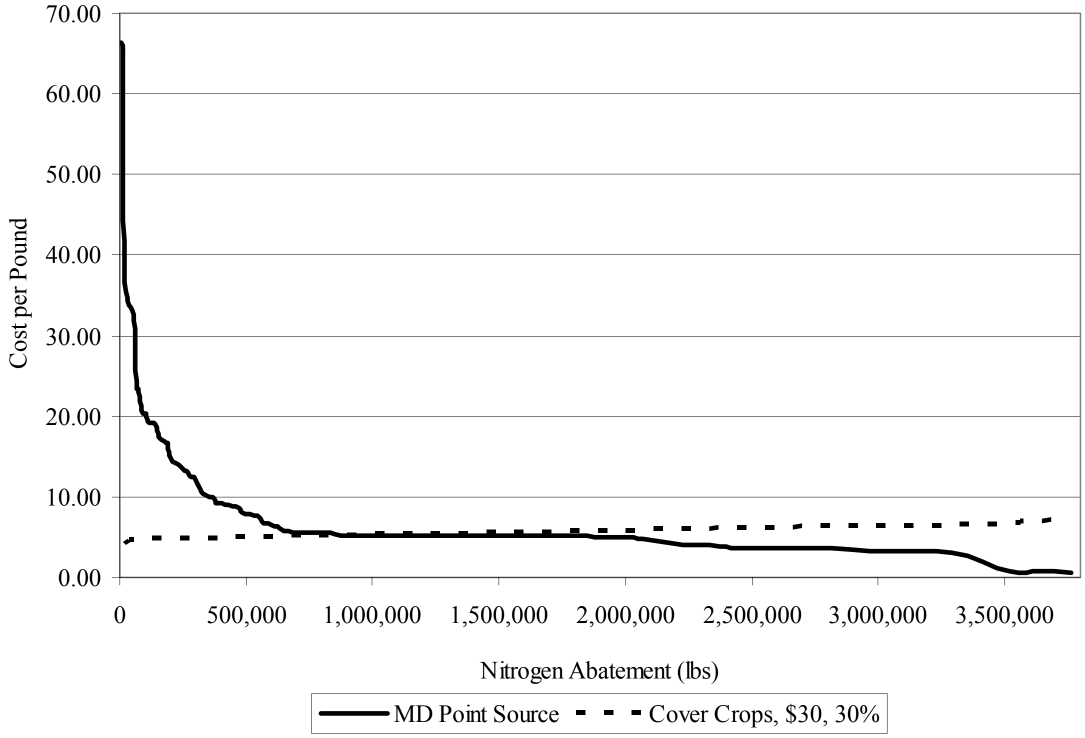

Figure 2. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops, Traded Within Maryland

Note: $30 per acre and 30 percent reduction of nitrogen.

cover crop abatement moving from right to left and POTW abatement left to right. The total abatement target equals the amount of abatement that would be achieved by the POTWs if they all upgraded to ENR. In the case presented here—30 percent efficiency and $30 per acre for the payment (see equation 2)—there is little variation in the abatement cost from cover crops because the high cost non-point sources are not relevant. The costs of abating the quantity on the horizontal axis are minimized when the incremental costs from the two different sources are equal, where the marginal abatement cost curves intersect.

There are greater differences in cost per pound of nitrogen abatement for POTWs than for cover crops (Figure 2). If there were no trading and all 64 POTWs were upgraded to ENR, then the abatement in nitrogen would be 3,763,387 pounds (Table 3). When trading is allowed, with the goal of abating the same amount of nitrogen, then only 16 of the least expensive POTWs are built and they abate 2,948,726 pounds of nitrogen. The remainder of the abatement (814,661 pounds) is achieved by planting 111,419 acres of cover crops. Instead of spending $263,742,760 on POTWs, only $136,600,000 is spent on the 16 POTWs. The cost of planting cover crops is $49,951,337. The total cost or abatement under this shared reduction in loading of nitrogen is $186,551,337, or 71 percent of the allocated amount from the Flush Tax legislation, saving over $77 million.

Trading can be limited to within each of the four major watersheds in Maryland. The goal is still 3,763,387 pounds of abatement, but expensive POTWs can be traded for cover crops only within the respective watershed (Table 4). The differences among watersheds are dramatic.

The POTWs of the Eastern Shore and Potomac watersheds are smaller in terms of average abatement per POTW. In these two more rural watersheds, there is a greater potential of nitrogen abatement from the use of cover crops than from upgrading POTWs from BNR to ENR (Figures 3

Table 3. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops

	Total Available		Efficient Combinations		% of Efficient Combinations			
	Point Source	Cover Crops	Point Source	Cover Crops	Point Source	Cover Crops	Total	% of Total
No. of units	64 POTWs	1,165,079 ac	16 POTWs	111,419 ac	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	2,948,726	814,661	78%	22%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$136,600,000	$49,951,337	n/a	n/a	$186,551,337	71%
Avg. annual cost/lb	n/a	n/a	3.72	4.92	n/a	n/a	n/a	n/a

Note: At $30/acre and 30 percent reduction efficiency, statewide trading.

and 4). It is feasible to plant almost one million acres of cover crops in these two watersheds. Under trading for the Eastern Shore watershed, only one POTW is upgraded. Seventy-six percent of the Eastern Shore's abatement goal is met by planting cover crops. For the Potomac watershed, six of 23 possible POTWs are upgraded to reach 75 percent of its abatement goals, with 25 percent of the abatement coming from the use of cover crops. The cost savings for these two watersheds, by allowing trading, are significant. One hundred percent of the abatement goals for the Eastern Shore and Potomac watersheds can be met at only 39 percent and 64 percent of the costs, respectively.

The POTWs of the Western Shore and Patuxent drain into more urban watersheds. In these watersheds, there is a greater potential of nitrogen abatement from upgrading POTWs from BNR to ENR than from the use of cover crops (Figures 5 and 6). As compared to the one million acres of cover crops in the two rural watersheds, it is only possible to plant approximately 200,000 acres of cover crops in these watersheds. One-third of 15 POTWs are upgraded in the Western Shore watershed to meet 87 percent of its abatement goals, and 4 of 7 POTWs are upgraded in the Patuxent watershed to meet 92 percent of its goals. Because these two watersheds are more urban, the cost savings are not as dramatic as with the Eastern Shore. However, 100 percent of the abatement goals for the Western Shore and Patuxent watersheds can be met at 86 percent and 84 percent of the costs, respectively.

When trading is allowed across the state (Table 3) or restricted to only within the four watersheds (Table 4), the cost savings are identical at 71 percent of the cost when all POTWs are upgraded. This would suggest that trading could be pursued through the watershed level. In this way, the problems associated with "hot spots" can be mitigated. Using the same logic, trading within the 10 tributaries in Maryland could be examined. The problems of "hot spots" would be further reduced, but whether the cost savings would be as great would need to be determined.

Further Considerations

Accounting for differences in abatement costs demonstrates the savings available with the kind of administered trading considered here. Given that this is not a true incentive-based mechanism, it is possible that much higher savings would be available. Even so, various technical issues create barriers even to the simple arbitraging that we have discussed. We explore some of the more salient issues that would arise in the implementation of an administered trading scheme. These issues are not exhaustive, but they reveal the complexity of the problem.

Uncertainty about Abatement Costs with Cover Crops

In our research, we assumed two different costs of subsidies to farmers to plant cover crops—$30 per acre and $20 per acre—and two different levels of effectiveness from the cover crops—15 percent and 30 percent abatement in nitrogen. We also assume a 20 percent charge in administering this program, which is likely to be by the state department of agriculture and its soil conservation districts or by the state natural resource and conservation service. Cover crop abatement effectiveness is often tied to planting date. In Mary-

Table 4. Efficient Allocations of Nitrogen Abatement Between Point Sources and Cover Crops ($30 per acre and 30 percent reduction efficiency) in Maryland, When Traded on a Statewide Basis

	Total Available		Efficient Combinations		% of Efficient Combinations			
Watersheds	Point Source	Cover Crops	Point Source	Cover Crops	Point Source	Cover Crops	Total	% of Total
Eastern Shore								
Number of units	19 POTWs	666,635 acres	1 POTW	33,415 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	322,808	3,411,299	78,174	244,634	24%	76%	322,808	100%
Capital cost ($)	$51,111,075	n/a	$5,000,000	$14,980,889	n/a	n/a	$19,980,889	39%
Avg. annual cost/lb	n/a	n/a	$5.14	$4.92	n/a	n/a	n/a	n/a
Potomac								
Number of units	23 POTWs	303,298 acres	6 POTWs	43,597 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	1,248,726	1,851,779	936,273	312,453	75%	25%	1,248,726	100%
Capital cost ($)	$68,033,645	n/a	$24,000,000	$19,545,634	n/a	n/a	$43,545,634	64%
Avg. annual cost/lb	n/a	n/a	$2.06	$5.02	n/a	n/a	n/a	n/a
Western Shore								
Number of units	15 POTWs	142,927 acres	5 POTWs	28,449 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	1,472,377	701,349	1,274,426	197,951	87%	13%	1,472,377	100%
Capital cost ($)	$104,999,020	n/a	$78,000,000	$12,754,283	n/a	n/a	$90,754,283	86%
Avg. annual cost/lb	n/a	n/a	$4.91	$5.17	n/a	n/a	n/a	n/a
Patuxent								
Number of units	7 POTWs	52,218 acres	4 POTWs	7,740 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	719,476	307,059	659,853	59,623	92%	8%	719,476	100%
Capital cost ($)	$39,599,020	n/a	$29,600,000	$3,470,291	n/a	n/a	$33,070,291	84%
Avg. annual cost/lb	n/a	n/a	$3.60	$4.67	n/a	n/a	n/a	n/a
Sum of Watersheds								
Number of units	64 POTWs	1,165,078 acres	16 POTWs	113,201 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	2,948,726	814,661	78%	22%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$136,600,000	$50,751,097	n/a	n/a	$187,351,097	71%
Avg. annual cost/lb	n/a	n/a	$3.72	$5.00	n/a	n/a	n/a	n/a

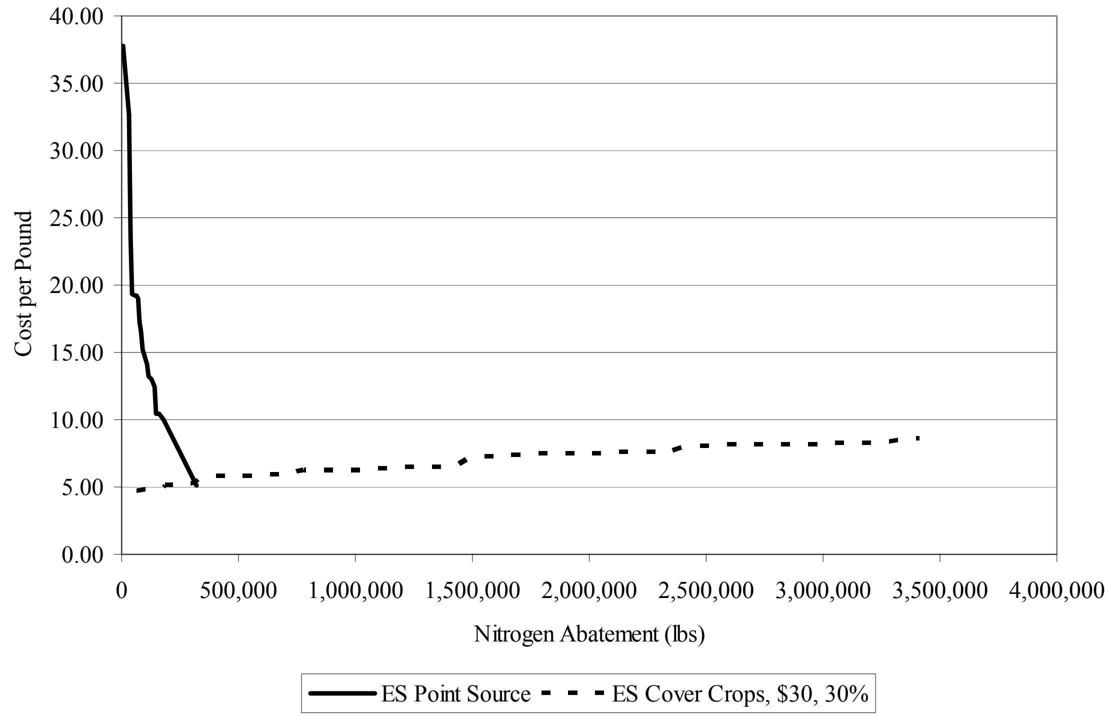

Figure 3. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops, Traded Within the Eastern Shore Watershed

Note: $30 per acre and 30 percent reduction of nitrogen.

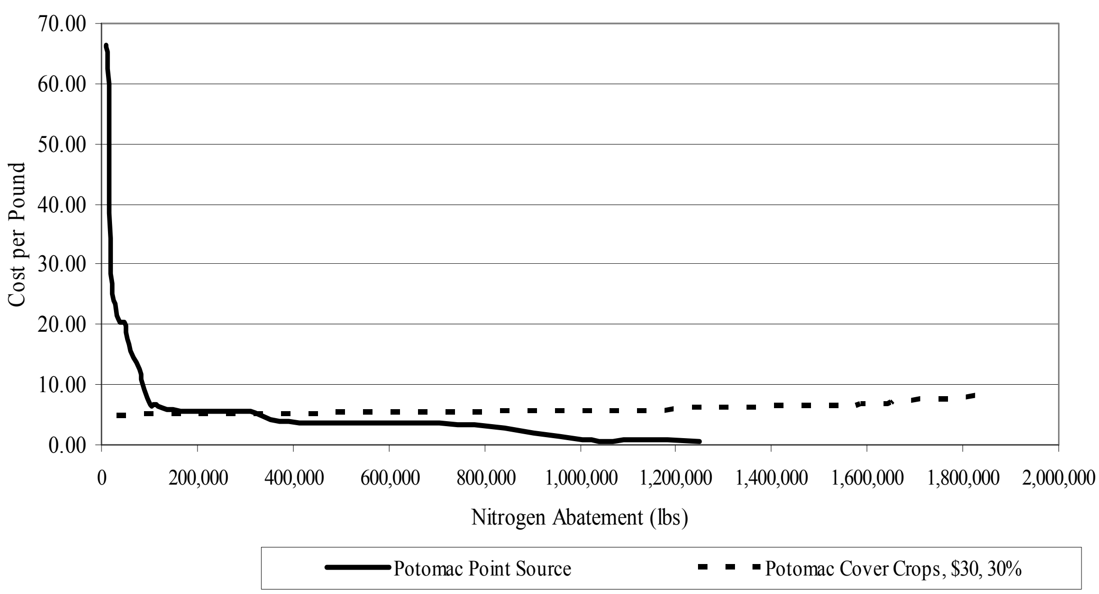

Figure 4. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops, Traded Within the Potomac Watershed

Note: $30 per acre and 30 percent reduction of nitrogen.

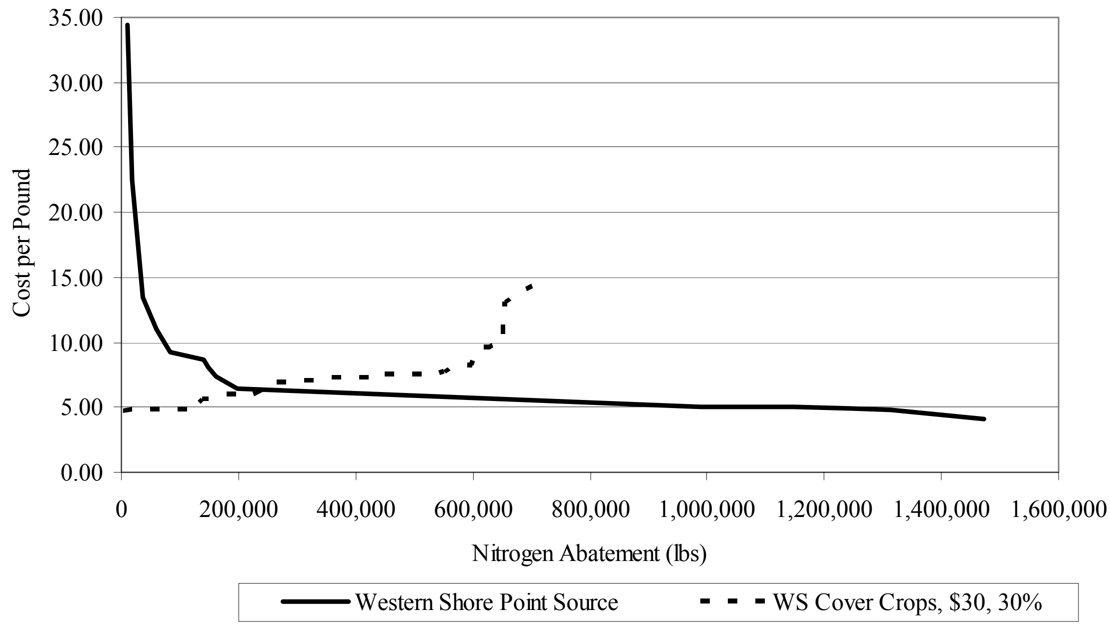

Figure 5. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops, Traded Within the Western Shore Watershed

Note: $30 per acre and 30 percent reduction of nitrogen.

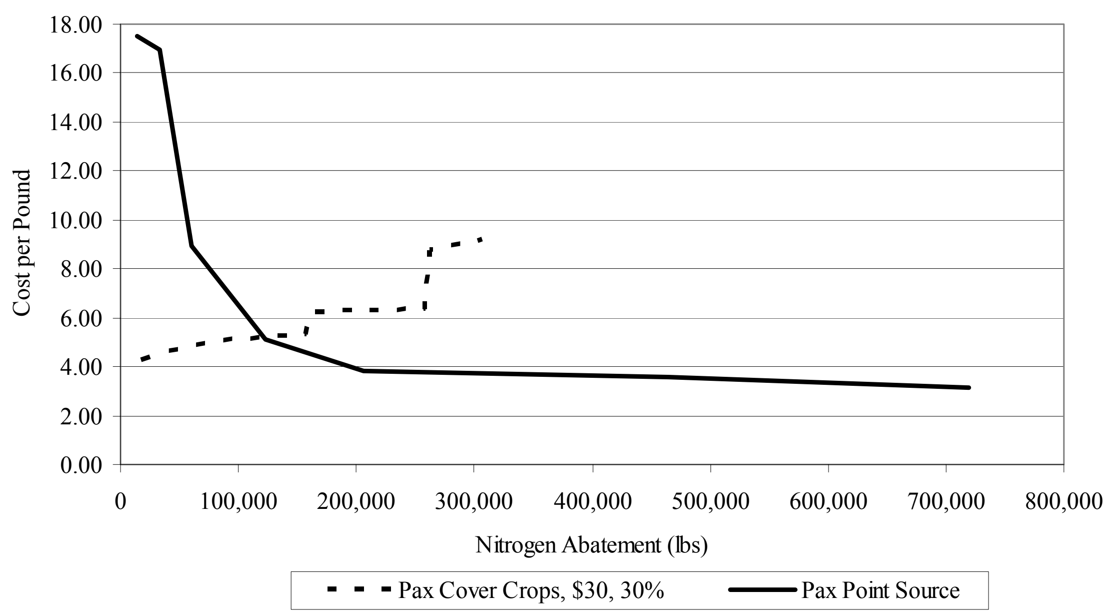

Figure 6. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops, Traded Within the Patuxent Watershed

Note: $30 per acre and 30 percent reduction of nitrogen.

land, it is assumed that cover crops planted before October 1 have a 30 percent abatement effectiveness and those planted after that date, 15 percent.

The relative attractiveness of cover crops versus improvements in POTWs depends on farmers' responses to these subsidies and how quickly they can get the cover crop planted (Table 5). The most optimistic assumption about farmer behavior ($20 per acre and 30 percent nitrogen reduction from early planting) leads to only 9 POTWs being upgraded and 330,278 acres of cover crops, with savings of 44 percent. The most pessimistic assumption about farmer behavior ($30 per acre and 15 percent nitrogen reduction from late planting) leads to 32 POTWs being upgraded and only 89,763 acres of cover crops, for a 17 percent cost savings. These differences are further complicated by differences in implementations for POTW upgrades and cover crop adoption. The upgrade is a one-time permanent decision and the cover crop adoption decision is annual.

The costs of abatement from cover crops have been computed on the assumption that cover crop plantings result in reductions in loadings as rapidly as POTW abatement. One of the biggest differences between point and non-point emissions is the lag between changes in abatement and changes in loadings to the Bay (see Phillips and Lindsey 2003). Increases and decreases in point source emissions are immediately transformed to corresponding changes in nitrogen in the Bay and its tributaries. Depending on the means of transport of non-point emissions, non-point source abatement can take anywhere from days to decades to impact the Bay. When nitrogen is part of surface water runoff, the lag time can be quite short. Nitrogen that is transported in groundwater may take up to 50 years to reach the Bay, with a median lag of about 11 years.[9] Given that about half of the nitrogen reaches the Bay through groundwater contribution to streams, this lag needs to be considered in understanding choices between point and non-point source abatement.

Hot Spots

In trading at the most aggregated level of Maryland, we implicitly assume uniform mixing of pollutants. Naturally, the broader the trading region the greater will be the gains from trading. However, increasing the size of the trading region enhances the potential for "hot spots," i.e., smaller areas that experience an increase in nitrogen pollution.

Table 3 shows the gains from trading expensive upgrades of POTWs for cover crops on a statewide basis. The statewide goal of abating 3,763,387 pounds of nitrogen is met with reductions in costs of 29 percent. However, there are differences in abatements by watershed (not shown). Specifically, abatement through this trading scheme as compared to what would have occurred with the enactment of the Flush Tax would be 77 percent, 103 percent, 109 percent, and 95 percent of the abatement goals for the Eastern Shore, Patuxent, Potomac, and Western Shore watersheds, respectively. The Eastern Shore and Western Shore watersheds will actually experience a relative increase in nitrogen pollution (or a smaller level of abatement) compared to what would have occurred with the Flush Tax. As shown in Table 4, this problem can be rectified by trading on a watershed basis, with only slight increases in costs. However, that could lead to inequities among tributaries. And, if trading occurred within tributaries, then individual cities or counties could complain about their POTW not being upgraded.

Phosphorus Emissions

When the goal is to maximize nitrogen reduction given the funding from the Flush Tax, phosphorus reductions suffer. Phosphorus loadings also contribute to the over-nutrification of the Bay. Hence one of the advantages of an "engineering fix" such as ENR or BNR is that systems can be designed to abate several nutrients at once, such as nitrogen and phosphorus. It may be expensive but it is feasible. The disadvantage of a "biological fix" is that it may not be feasible to abate more than one nutrient. Cover crops are a good example. They work well to inexpensively reduce nitrogen pollution, but not so well in reducing phosphorus pollution.

[9] These figures are taken from the summary document by Phillips and Lindsey (2003).

Table 5. Efficient Allocation of Nitrogen Abatement Between Point Sources and Cover Crops in Maryland

	Total Available		Efficient Combinations		% of Efficient Combinations			
Cover Crop Assumptions	Point Source	Cover Crops	Point Source	Cover Crops	Point Source	Cover Crops	Total	% of Total
$30/acre, normal planting (15% N reduction)								
Number of units	64 POTWs	1,165,079 acres	32 POTWs	89,763 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	3,432,747	330,640	91%	9%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$179,600,000	$40,242,569	n/a	n/a	$219,842,569	83%
Avg. annual cost/lb	n/a	n/a	$4.20	$9.77	n/a	n/a	n/a	n/a
$20/acre, normal planting (15% N reduction)								
Number of units	64 POTWs	1,165,079 acres	23 POTWs	154,411 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	3,209,091	554,296	85%	15%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$155,600,000	$46,150,465	n/a	n/a	$201,750,465	76%
Avg. annual cost/lb	n/a	n/a	$3.89	$6.69	n/a	n/a	n/a	n/a
$30/acre, early planting (30% N reduction)								
Number of units	64 POTWs	1,165,079 acres	16 POTWs	111,419 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	2,948,726	814,661	78%	22%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$136,600,000	$49,951,337	n/a	n/a	$186,551,337	71%
Avg. annual cost/lb	n/a	n/a	$3.72	$4.92	n/a	n/a	n/a	n/a
$20/acre, early planting (30% N reduction)								
Number of units	64 POTWs	1,165,079 acres	9 POTWs	330,278 acres	n/a	n/a	n/a	n/a
Abatement (lbs)	3,763,387	6,271,486	1,533,474	2,229,914	41%	59%	3,763,387	100%
Capital cost ($)	$263,742,760	n/a	$49,600,000	$98,713,408	n/a	n/a	$148,313,408	56%
Avg. annual cost/lb	n/a	n/a	$2.60	$3.55	n/a	n/a	n/a	n/a

Note: Statewide in Maryland.

With 100 percent enactment of the Flush Tax legislation—that is, upgrading all POTWs—phosphorus would be abated by 658,593 pounds. Using trades, based on nitrogen abatement as illustrated in Table 3, the amount of phosphorus abated would be only 533,200 pounds. The 16 POTWs that are upgraded abate 516,028 pounds of phosphorus, but the 111,419 acres of cover crops are not as effective, abating only 17,172 pounds of phosphorus.

The disproportionate reduction in nitrogen and phosphorus loadings by POTWs and cover crops, combined with the differences in abatement costs, suggests that there are gains from trade, but some knowledge of the ecological marginal rate of substitution between nitrogen and phosphorus is required. That is, we would like to know the rate of substitution between nitrogen and phosphorus that keeps a key ecological goal, such as dissolved oxygen, constant. Assuming this rate to be constant over a small range, we could then convert changes in phosphorus to changes in nitrogen that are ecologically neutral. This would permit us to factor in differential changes in phosphorus.

Uncertainty about Loadings

Uncertainty is an important aspect of the debate about point versus non-point sources and eventually brings up the idea of the trading ratio. The trading ratio is the number of units of non-point source abatement that must be provided for a one-unit reduction in point sources. In the simplest of environments, where abatement of point and non-point pollution provides certain reductions in ambient levels of pollution and there is uniform mixing of pollutants from different sources, the trading ratio should be one. The argument is then made that, because of the greater uncertainty in abating non-point sources, trading ratios should be greater than one. For example, a trading ratio of two means that abating two pounds of nitrogen from a non-point source is equal to abating one pound of nitrogen from a point source. King and Kuch (2003) suggest that the typical trading ratio lies between one and four. Horan (2001) gives trading ratios between one and three. The effect of a trading ratio greater than one is to make non-point sources more expensive and, other things equal, to restrict their use.

This argument appears solid only because it is based on what happens to abatement, not emissions. To recognize the difficulty with this argument, we focus on the primary task of Bay pollution control, that is, reduction in emissions of nutrients. Due to weather, emissions are likely to be random. We characterize randomness by discrete increases or decreases in emissions. By definition, these increases and decreases cancel out over time.[10]

In the situation where a policy attempts to reduce the random variation of emissions as well as mean emissions, control measures should adopt a trading ratio to encourage the abatement of the more random emissions. In the case of the Chesapeake Bay, emissions are more random from non-point sources than point sources. This follows as long as greater abatement of non-point sources reduces the randomness of non-point emissions, an assumption that is reasonable.[11] When resources are devoted to abating non-point emissions, there are two gains: lower mean emissions and less randomness. With point source abatement, we get only reductions in mean emissions. Reductions in point source randomness is unchanged since it is defined as "relatively certain." However, more important, the randomness from non-point sources is left unchanged.

Consider non-point nutrient emissions from 1,000 acres of agricultural land. Each acre emits an average of 8 pounds of nitrogen, with an equal chance of emitting 4 or 12 pounds. The emissions from this farm will range from 4,000 to 12,000 pounds, with a mean of 8,000 pounds. A local POTW has emissions of 15,000 pounds with little randomness. Abatement costs are similar for the POTW and cover crops. Total emissions from these two sources are 23,000 pounds, with a range of from 19,000 to 27,000 pounds. When cover crops are used for abatement, the loss per acre is reduced to 5 pounds, but with equal likelihood the loss can be 2.5 or 7.5 pounds. The loadings from this farm will now range from 2,500 to 7,500 pounds, with a mean of 5,000 pounds. Total emissions from the two sources are 20,000,

[10] We view the problem ex ante but compound the possible uncertainties from different sources, such as weather, how well technology works, etc., into one uncertainty. Malik, Letson, and Crutchfield (1993) consider several sources of uncertainty.

[11] See Shortle (1987) for a mathematical proof of this assertion. A more general statement can be found in Hennessy and Feng (2008).

with a range of from 17,500 to 22,500 pounds. The use of cover crops has reduced the mean and range of emissions.

Suppose instead that we choose to abate 3,000 pounds from the POTW. When the point source is adopted, we retain the randomness from non-point sources. Total emissions from the two sources would now be 20,000, with a range of from 16,000 to 24,000 pounds. When the non-point source is abated, we reduce both the mean and the randomness. So instead of advocating for a trading ratio of greater than one, as mentioned previously, a trading ratio of less than one is actually the preferred option to improving water quality.[12]

The arguments about the correct trading ratio hinge on the convexity of the damage function in loadings. The relevance of convexity depends on the scale of the trades, which depends on the application. To begin with, nutrient flow to the Bay is made up of human-induced emissions and natural contributions. The current Chesapeake Bay agreement calls for reducing nitrogen from 285 million pounds to 175 million pounds. In this context, the difference in emissions caused by uncertain non-point source emissions is quite small. From Table 5, we see that the maximum abatement from non-point sources is about 3 million pounds. Under current circumstances this amounts to about one percent of total current nitrogen emissions. This change in emissions represents an amount so small that curvature of abatement costs and—more important in this case—the convexity of the damage function, can hardly have a role in determining the exchange of non-point and point emission reductions. At least from the perspective of uncertainty in nutrient emissions in the Chesapeake Bay, there is no reason not to trade point and non-point source abatement one for one.

Conclusion

In this paper we present evidence that under an administered trading system, where the responsible public agency selects lower cost abatement, there are in principle savings that could enhance Bay water quality. There are naturally barriers to these trades. These barriers are evident in the paucity of trading for nutrient abatement across the country. Reducing the barriers to administered trading, such as we have analyzed, can provide some gains. But the real gains, those that come from true incentive-based mechanisms, require substantial improvements in our scientific understanding of the connection between non-point source abatement and the reduction of nutrients to the Bay. Despite the difficulty in obtaining complete understanding, it makes sense to continue to explore and develop opportunities to exploit differences in abatement costs either through administered trading or through the use of true incentive-based mechanisms.

[12] This argument is predicated on the assumption that the randomness of the non-point system is viewed in aggregate. In other words, the randomness of the emissions from the previous crop (e.g., corn) is not separated from the randomness of the abatement associated with the cover crop (i.e., winter rye). When viewed over many years, the aggregate view is more appropriate.

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