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Agricultural Costs of the Chesapeake Bay Total Maximum Daily Load

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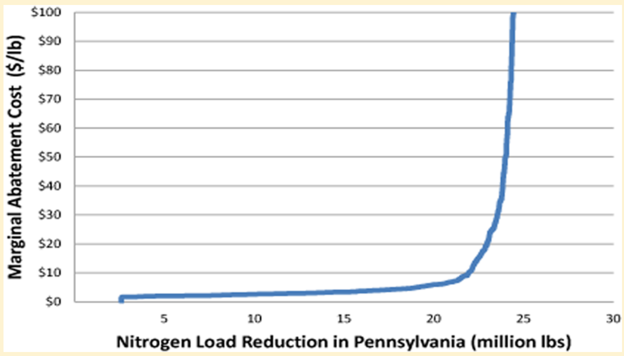
Supporting Information

ABSTRACT: This study estimates costs to agricultural producers of the Watershed Implementation Plans (WIPs) developed by states in the Chesapeake Bay Watershed to comply with the Chesapeake Bay total maximum daily load (TMDL) and potential cost savings that could be realized by a more efficient selection of agricultural Best Management Practices (BMPs) and spatial targeting of BMP implementation. The cost of implementing the WIPs between 2011 and 2025 is estimated to be about \$3.6 billion (in 2010 dollars). The annual cost associated with full implementation of all WIP BMPs from 2025 onward is about \$900 million. Significant cost savings can be realized through careful and efficient BMP selection and spatial targeting. If retiring up to 25% of current agricultural land is included as an option, Bay-wide cost savings of about 60% could be realized compared to the WIPs.



INTRODUCTION

On December 29, 2010, the U.S. Environmental Protection Agency (USEPA) issued the Chesapeake Bay total maximum daily load (TMDL). The TMDL specifies reductions of nitrogen, phosphorus, and sediment across Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia, and sets pollution limits necessary to meet applicable water quality standards in the Bay and its tidal rivers and embayments. All pollution control measures needed to comply with the TMDL for the Bay and its tidal rivers are to be in place by 2025. The TMDL is required under the federal Clean Water Act and responds to consent decrees in Virginia and the District of Columbia from the late 1990s.

Agriculture constitutes 22% of the Chesapeake Bay's watershed land area, making it the second largest land use following forests and open wooded areas. Agricultural activities are estimated to contribute approximately 44% percent of nitrogen and phosphorus loads, and 65% of the sediment loads delivered to the Bay, making agriculture the largest source of nutrients and sediments to the Bay.[1] The TMDL calls for reducing nitrogen, phosphorus, and sediment loads from agriculture by 37%, 29%, and 28%, respectively, relative to 2009 baseline loads and by 34%, 29%, and 22%, respectively, relative to 2011 baseline loads.[2] The allocation of these reductions varies across political jurisdictions and major basins (allocations by jurisdiction are shown in Table 1). The means by which agricultural reductions are to be achieved in each jurisdiction are described in Watershed Implementation Plans

Table 1. TMDL Agricultural Reduction Targets[a]

	target (thousands of lbs/year)		
state	nitrogen	phosphorus	sediment
Delaware	870	44	0[b]
Maryland	3559	83	0[b]
New York	1095	109	18 314
Pennsylvania	23 735	794	466 487
Virginia	6672	1850	678 322
West Virginia	177	53	34 725

[a]Source: Derived from data from Chesapeake Bay Program.[2] [b]The zeros for sediment for Delaware and Maryland mean that agricultural pollution goals have already been met and exceeded in these two cases. Sediment pollution is 9.44 million lbs/year below the goal for Delaware and 131.93 million pounds/year below the goal for Maryland.

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(WIPs) developed by the six Bay states in collaboration with USEPA.

Significant concerns have emerged about the costs of achieving the Chesapeake Bay TMDL and who will pay for them.[3] The TMDL and its allocation among jurisdictions and source sectors (agriculture, wastewater, etc.) were set prior to estimation of the costs of implementing the TMDL, a practice that is common in setting TMDLs.[3] An important factor in establishing load allocations according to the USEPA TMDL documentation was that allocations should result in all areas of the Bay meeting standards for dissolved oxygen, chlorophyll a, and water clarity.[4,5] Relative effectiveness, or how geography influences the impact of nitrogen and phosphorus load changes, was also a factor in determining allocations. Once allocations by major basin and jurisdiction were determined by EPA, jurisdictions were responsible for detailing how they planned to meet their load and wasteload allocations in their WIPs. The WIPs were evaluated by EPA to address any deficiencies.[5]

The objectives of this study are to estimate (1) the costs to agricultural producers of the WIPs developed by the states to comply with the Chesapeake Bay TMDL and (2) agricultural cost savings that could be realized by a more efficient selection of agricultural BMPs and spatial targeting of BMP implementation than the selections specified in the WIPs. To our knowledge, no other published study has estimated these costs or potential cost savings for the Chesapeake Bay.

■ MATERIALS AND METHODS

Spatial and Temporal Distribution of BMPs. Under the Chesapeake Bay TMDL, load allocations are subdivided by jurisdiction and major river basin. These jurisdictions include Delaware, the District of Columbia, Maryland, New York, Pennsylvania, Virginia, and West Virginia. The District of Columbia is not included in our analysis because it has no agricultural lands. Each jurisdiction submitted Phase I and Phase II WIPs, which outline how each jurisdiction will achieve their nitrogen, phosphorus, and sediment pollution allocations. For agriculture, the WIPs consist of lists of best management practices (BMPs) that reflect state implementation goals for farmers. The BMPs analyzed are defined in Table S1, Supporting Information (SI). Although the Phase II WIPs are more detailed than the Phase I WIPs, they provide only limited details about where and when specific BMPs are to be implemented. This section describes our assumptions about the spatial and temporal distribution of BMPs.

The Chesapeake Bay Watershed Model (CBWM) is the major tool used by USEPA to assess the impact of the WIPs on pollution loads and compliance with the TMDL. The CBWM is a hydrological model that simulates and projects pollutant loads and how they move over and through the land and water in the Chesapeake Bay Watershed. Data and geographic management units from the CBWM Phase 5.3.2 are used in this study.[6] Land-river segments are the base modeling unit for the CBWM. Figure S1, SI shows Phase 5.3.2 land-river segments within the watershed. Counties form the basis of the land segmentation, with some counties further divided based on nutrient flows within counties. The river segmentation simulates river reaches of similar discharges of approximately 100 cubic feet per second and their associated watersheds. The intersection of the county-based land segmentation and watershed-based river segmentation results in the land-river segmentation for the CBWM. Nutrient flows are modeled within each of these land-river segments. Nutrient flows from individual land-river segments to the tidal waters of the Bay are simulated with delivery factors for each land−river segment and pollutant.

After eliminating land-river segments with no agricultural land, there are 2426 land-river segments to be analyzed. They include 28 in Delaware, 671 in Maryland, 143 in New York, 582 in Pennsylvania, 881 in Virginia, and 121 in West Virginia.[6] The CBWM identifies land according to sector-specific land uses. For agriculture, these land uses include animal feeding operations, row crops, hay, pasture, degraded riparian pasture, and nurseries. The CBWM also models whether a land-use is high-till or low-till for row crops and hay, and whether nutrient management is used on row crop, hay, and pasture land. This results in 16 agricultural land uses, excluding concentrated animal feeding operations (CAFOs), which are treated as point sources of pollution by USEPA. Watershed-wide, direct discharges from CAFOs (e.g., through a pipe or ditch) account for only about 2% of nitrogen and 3% of phosphorus delivered to the Bay.[2] Waste from CAFOs spread on cropland or pastureland accounts for much higher percentages of nutrient deliveries to the Bay (about 17% of nitrogen and 26% of phosphorus), but this waste is attributed in the CBWM to the farms that apply it to their fields, not to the CAFOs. As such, it is treated as a nonpoint pollution source in the CBWM and included in our analysis here.[2]

The Chesapeake Bay Program (CBP) proportional allocation rule is followed to distribute BMPs across land-river segments. This rule allocates BMPs according to the percentage of applicable land use acres within each land-river segment modeling unit.[6] Such a rule was necessary because state WIPs were not spatially specific at the land-river segment scale, the relevant management unit for the CBWM. The timing of BMP implementation affects both the cumulative (across years) benefits of the TMDL and the discounted present value of cumulative costs. While a variety of time paths are plausible, we assume that implementation increases linearly until full BMP implementation is reached in 2025. For example, if the 2025 implementation target is 250 acres and the 2011 baseline is 110 acres, implementation totals would be 120 acres in 2012, 130 acres in 2013, and so on (i.e., 10 additional acres each year based on the need to add 140 acres in 14 years). Another possibility would have been to choose a time path that adhered to the interim TMDL goal of having 60% of practices in place by 2017. However, in light of uncertainty about whether states will meet this interim goal, a linear assumption was chosen.

Agricultural BMP Costs. The cost of adopting a BMP can be calculated from three perspectives: costs to agricultural producers; costs to the government, including costs of financial and technical assistance; and costs to society at large, which include costs to producers, the government, and anyone else impacted directly or indirectly by the practice. The costs analyzed in this study are costs to agricultural producers implementing the BMPs, exclusive of any financial assistance from the government for adoption. Financial assistance reduces the net costs of adoption to producers, but not to society at large because taxpayers must cover the costs of that assistance.

The primary source for BMP cost data used in this study is the USEPA Chesapeake Bay Program (CBP). These estimates were developed for the CBP by Abt Associates for BMPs in the Phase II WIPs.[7] The primary data source for the Abt/USEPA cost estimates is Natural Resource Conservation Service (NRCS) financial assistance payment schedules. These costs include maintenance costs, where applicable. We rely on the Abt/USEPA BMP unit cost estimates, with a limited number of adjustments and exceptions. Cost estimates are confined to well-established BMPs and thus exclude interim or newly developed BMPs that have not yet been approved for nutrient credit within the CBWM. BMP cost estimates include the opportunity cost of any land taken out of production. Nonfinancial costs to farmers (e.g., perceived risk) are not included.

In estimating BMP costs we do not allow net economic benefits to producers or cost savings from decreased implementation from the baseline year through 2025. This is consistent with our approach of choosing an upward bias in cost estimates when we have unavoidable ambiguities, and our general view of the cost estimates as an upper bound. If net costs are believed to be zero or negative for a BMP (examples include tillage practices,[8] cropland irrigation management, dairy precision feeding, and phytase), the net BMP cost is set to $0. For this reason, the estimates here can be viewed as upper bounds on the financial costs of BMPs.

WIP Cost Estimates. We utilized individual BMP costs to estimate total agricultural costs of the WIPs using two methods. The first method estimates the present value of the costs of achieving 2025 BMP implementation levels starting from a baseline year. Consistent with the methodology used by CBP and Abt Associates in estimating costs of individual BMPs, WIP costs are discounted here to the baseline year at an annual real discount rate of 7%. A 7% real discount rate is considered by the U.S. Office of Management and Budget (OMB) to be the "base case" for regulatory analysis.[9] OMB also recommends calculating a second set of cost estimates using a 3% real discount rate,[9] but CBP did not do this for individual BMPs.

We use two baseline years, 2009 and 2011. Given that the TMDL was issued at the end of 2010, and producers did not have a realistic opportunity to implement new practices until 2011, a 2011 baseline is logical. USEPA uses a 2009 baseline; our understanding is that this choice was based on available data at the time the TMDL was issued. These present value estimates consider only the costs of required BMP implementation through 2025 and nothing afterward. The second method estimates the annualized costs associated with full implementation of all WIP BMPs. These costs were calculated by subtracting 2011 baseline implementation from total 2025 implementation prescribed in the state WIPs for each BMP and multiplying this figure by the annual BMP cost. These annual cost estimates can be interpreted as the cost per year of full implementation at 2025 levels.

BMP Cost-Effectiveness. A second objective of this study is to explore the potential for improving the cost-effectiveness of agricultural BMP implementation relative to agricultural practices specified in the WIPs. Agricultural cost savings may potentially be achieved through a combination of overall BMP selection, emphasizing greater use of BMPs that are relatively more cost-effective in reducing nutrient and sediment pollution and BMP targeting, emphasizing the placement of BMPs in locations that have greater impact on water quality. The cost-effectiveness of each BMP is estimated by combining cost data with parameter values from the CBWM on BMP effectiveness. In the CBWM, most agricultural BMPs are assigned "reduction efficiencies" for nitrogen, phosphorus, and sediment according to the average pollutant-reducing capability of that BMP. This efficiency is the estimated fractional reduction in edge-of-segment loads for each pollutant—nitrogen (N), phosphorus (P), and sediment (TSS). Edge-of-segment loads are the amount of each pollutant that reaches the boundary waters for that land-river segment. Because nutrient flows to the Bay vary across land-river segments, all load reductions were translated into delivered load reductions by the use of delivery factors from the CBWM for each pollutant and land-river segment.

All agricultural BMPs that had complete data (BMP cost, reduction efficiency, and baseline land use) were included in the cost-effectiveness assessment. Some BMPs were excluded from further analysis because they were unambiguously dominated by other BMPs. Alternative watering is an example. While figuring prominently in the WIPs, this BMP is dominated by cheaper and more effective alternatives such as prescribed grazing. In other words, our cost-effective portfolios would have eliminated such BMPs had they been included in the analysis. Stream access control cost estimates include costs for watering facilities.

Two scenarios are analyzed reflecting two alternative approaches to reducing agricultural NPS loadings. One is to implement BMPs on working agricultural lands. The second is to convert cropland to alternative uses, including lower intensity agricultural uses. Thus, for scenario one, BMPs that take agricultural land out of crop production (such as buffers, land retirement, and wetland restoration) are excluded from analysis. The second scenario converts up to 25% of applicable land use acres in each land-river segment to either hay without nutrients or to forest, according to CBWM rules. This 25% is assumed to be net of any slippage/leakage. Land converted to hay without nutrients is classified as land retirement in the CBWM, whereas land converted to forest is classified as tree planting in the CBWM.[6] Both costs are annualized estimates over the lifespan of the BMP of converting land to either hay without nutrients or forested land, including the NASS state average soil rental rate as the opportunity cost of the land. In this study, both of these land conversions are referred to as land retirement.

Using two scenarios enables us to compare the effect of land retirement practices on reductions and costs in each jurisdiction. The 25% land retirement figure is motivated by, and consistent with, the general upper bound of 25% on the farmland in a county that can be enrolled in U.S. Department of Agriculture's (USDA) Conservation Reserve Program (CRP) and/or Wetland Reserve Program (WRP).[10] Van Houtven et al., in their analysis of nutrient credit trading in the Chesapeake Bay Watershed, also use a 25% limit on land retirement.[11] One drawback of selecting a percentage limit is that it may not be the economically efficient percentage. The economics of agricultural land use in the Bay region generally, and as affected by the TMDL, are complex. Analyzing land use choices presents many challenging data and modeling issues that are beyond the scope of this study.[12]

Not all land retirement reductions were necessarily included in our results, as marginal costs for land retirement varied across land-river segments. Only cost-effective land retirement solutions according to our MAC sorting criteria were included in the solutions. We followed CBP accounting rules for combining practices. Within these rules, each BMP can be applied to a certain set of acceptable land uses according to the BMP's specific purpose. For example, prescribed grazing can only be applied to pasture and nutrient management pasture land uses, whereas conservation plans can be applied to most agricultural land uses. There are also rules within the CBWM regarding which BMPs can be applied together on the same acres and remain eligible for loading reductions. Those BMPs that can be applied in combination are referred to by the CBP

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Table 2. Annual Costs of All New WIP Agricultural BMP Implementation Beyond 2011 Baseline ($ million)[a]

BMP	Delaware	Maryland	New York	Pennsylvania	Virginia	West Virginia	Chesapeake Bay	percentage of bay total
alternative watering	$0	$0	$15.6	$85.2	$0	$0	$100.7	11.2%
ammonia emissions reduction – alum	0	0.8	0	0.5	1.5	0	2.8	0.3%
ammonia emissions reduction – biofilters & lagoon	0.2	0	0	4.5	0	0	4.7	0.5%
animal waste management systems – livestock	2.3	27.7	3.4	105.0	96.2	1.8	236.5	26.2%
animal waste management systems – poultry	3.1	0.7	0.1	4.7	8.7	2.0	19.2	2.1%
barnyard runoff	0.2	0.2	0	2.7	2.3	0	5.4	0.6%
capture & reuse	0	2.8	0	0.9	4.0	0	7.8	0.9%
carbon sequestration	0.0	0.0	0	1.4	0	0	1.5	0.2%
commodity cover crops	0.4	0	0.0	13.5	6.0	0.3	20.2	2.2%
conservation plan	0.3	0.7	0.8	2.9	1.8	0	6.5	0.7%
conservation tillage	0	0	0	0	0	0	0	0%
continuous no-till	0	0	0	0	0	0	0	0%
cover crops	1.1	10.3	2.2	13.2	19.1	0	45.9	5.1%
cropland irrigation management	0	0	0	0	0	0	0	0%
dairy precision feeding	0	0	0	0	0	0	0	0%
decision agriculture	5.2	18.4	1.0	2.5	5.3	0	32.3	3.6%
enhanced nutrient management	0	0.5	1.8	14.5	0.6	0	17.4	1.9%
forest buffers	0.5	0.2	1.3	23.2	7.0	0.4	32.4	3.6%
grass buffers	0.8	0.2	2.0	5.0	8.0	0	15.9	1.8%
horse pasture management	0	0.1	0.0	0	0.6	0	0.8	0.1%
land retirement	0.1	2.7	0.4	7.5	1.8	0.1	12.5	1.4%
liquid/poultry manure injection	0	11.3	9.0	2.1	0	0	22.3	2.5%
loafing lot management	0	0.3	0.8	0	0	0	1.1	0.1%
manure transport – inside chesapeake bay watershed	0	0.4	0	0	0.2	0	0.5	0.1%
manure transport – outside chesapeake bay watershed	2.6	0.5	0	6.1	2.1	0.6	11.9	1.3%
mortality composters	0	0	0.3	1.9	22.7	0.8	25.7	2.8%
nutrient management	0	0	0	0	0.8	0.7	1.5	0.2%
poultry phytase	0	0	0	0	0	0	0	0%
swine phytase	0	0	0	0	0	0	0	0%
precision intensive rotational grazing	0.1	0.3	0	26.3	0	0	26.7	3.0%
prescribed grazing	0	0.2	2.0	1.0	8.2	0	11.5	1.3%
stream access control with fencing	0	1.5	24.8	29.0	94.2	37.1	186.6	20.7%
stream restoration	0.5	0.6	2.0	0.3	0.8	0.1	4.3	0.5%
tree planting	0.0	0.9	0.0	4.9	9.2	0	15.1	1.7%
water control structures	0.2	0.3	0	0	0.0	0	0.5	0.1%
wetland restoration	1.8	1.4	3.8	19.4	6.2	0.1	32.7	3.6%
totals	**$19.4**	**$83.0**	**$71.2**	**$378.3**	**$307.4**	**$43.9**	**$903.2**	**100.0%**

[a]Note: Due to rounding, the total for each state may not equal the sum across BMPs for that state, and the Chesapeake Bay totals may not equal the sums across states. Because of rounding, the percentages in the final column sum to 100.3% rather than 100%.

as multiplicative. An example of multiplicative BMPs is cover crops applied to areas that include a conservation plan as well as enhanced nutrient management. Those BMPs that cannot be applied to the same acre are referred to by the CBP as additive. Continuous no-till is an example. Acres under continuous no-till are not also eligible for reductions from cover crops or nutrient management within the CBWM.[6]

Cost-Effective BMP Portfolios. A cost-effective BMP portfolio consists of a set of BMP types and locations that minimize the cost of achieving nutrient reduction goals. Identifying this portfolio would be straightforward if there was only one pollutant. A marginal abatement cost (MAC), defined as the cost per pound of pollutant reduced to the Chesapeake Bay, could be calculated for each BMP/land-river segment combination. BMP/land-river segment combinations could then be rank-ordered from low to high based on their MAC, with practices implemented until the required reduction is achieved. This process does not work for achieving N, P and TSS load reductions simultaneously because the cost-effective order of BMP implementation varies for each pollutant, and ordering matters because multiplicative BMPs decrease the nutrient reductions available when subsequent BMPs are implemented. A BMP within a land-river segment could be very cost-effective for reducing nitrogen but not very cost-effective for reducing phosphorus, or vice versa. A common ordering across the three pollutants is necessary for cost-effective portfolio calculations.

To achieve a common ordering, costs and load reductions were calculated in two ways: (1) P and TSS costs and load reductions were recalculated based on a cost-effective BMP ordering for N; and (2) N and TSS costs and load reductions were recalculated based on a cost-effective BMP ordering for P. For an N-based ordering in each jurisdiction, BMP/land-river segment combinations were implemented starting with the

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Table 3. Agriculture Cost Comparisons: WIPs versus Cost-Effective BMP Portfolios[a]

	annual cost ($ million)			percentage cost savings compared to the WIPs	
state	WIPs	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Delaware	$19.4	$3.9	$3.5	80%	82%
Maryland	$83.0	$12.8	$12.9	85%	84%
New York	$71.2	$51.8	$10.1	27%	86%
Pennsylvania	$378.3	NF[b]	$101.6	NF[b]	73%
Virginia	$307.4	NF[b]	$223.6	NF[b]	27%
West Virginia	$43.9	$16.8	$6.0	62%	86%
Chesapeake Bay	$903.2	$700.7[c]	$357.7	22%[c]	60%

[a]Note: Scenario 1 assumes no land retirement, whereas Scenario 2 involves up to 25% land retirement. [b]NF indicates "not feasible." Pennsylvania met 72% of its N target, 98% of its P target, and 97% of its TSS target in Scenario 1. Virginia met 62% of its P target and 94% of its TSS target in Scenario 1. [c]The Chesapeake Bay totals in Scenario 1 include Pennsylvania and Virginia, although these states do not meet their TMDL targets.

lowest N MAC and progressing onward in order with the next lowest, etc. All N reductions were summed along with accompanying P and TSS reductions for each BMP/land-river segment combination implemented. Implementation was stopped once TMDL load reduction targets were met for all three pollutants for that jurisdiction. A similar process was repeated for each P MAC curve. There were fewer TSS BMPs, so it was not necessary to recalculate N and P loads according to a TSS target. A TSS target resulted in a BMP ordering nearly identical to a P- based BMP ordering.

This process results in implementing the most efficient (lowest MAC) BMP/land-river segment combinations necessary to meet all load reduction targets at the jurisdiction scale for the pollutant on which the BMP ordering is based. These N- or P-based solutions were compared to determine which produced the lowest cost solution, and that one was then chosen. This process was utilized for both scenario one (no land retirement) and scenario two (25% land retirement). Cost-effective orderings were calculated at the jurisdiction scale because jurisdictions are responsible under the WIPs for achieving their load allocations. Orderings could be carried out at a more spatially disaggregated level (e.g., by basin within each jurisdiction), but that would limit the usefulness of this cost-effective BMP portfolio exercise because it would constrain the potential for concentrating BMPs in those basin(s) within a jurisdiction where MACs are lowest. The process used here is not guaranteed to minimize costs because there might be some ordering other than an N- or P-based ordering that yields even lower costs. However, if this process identifies cost savings compared to the WIPs, then one can conclude that these are lower bounds on the cost savings that could be achieved through targeting of BMP types and locations.

■ RESULTS

WIP Cost Estimates. The discounted total cost of the WIPs from the baseline year to full implementation in 2025 is about $3.6 billion utilizing the 2011 baseline, whereas the total cost utilizing the 2009 baseline is about $5.0 billion. It was assumed that reductions from implementation of the WIP BMPs met TMDL load reduction goals. The differences between 2009 and 2011 baseline estimates are driven by differences in BMP implementation levels as provided by CBP. Since baseline implementation is greater in 2011 than 2009, fewer BMPs need to be installed under the 2011 baseline scenario to reach the 2025 goals. Three BMPs (alternative watering, livestock waste management systems, and stream access control) account for the majority of baseline costs: about 14% (2009) and 11% (2011) for alternative watering; about 21% (2009) and 26% (2011) for livestock waste management systems; and about 30% (2009) and 21% (2011) for stream access control.

Annual cost estimates by BMP and jurisdiction for installing and maintaining all new implementation beyond the 2011 baseline are presented in Table 2. Any negative implementation is assigned a cost of $0. These annual cost estimates can be interpreted as the cost per year of full implementation at 2025 levels.

Estimated costs for full implementation of the WIPs are about $900 million annually. Jurisdiction-specific annual WIP cost estimates are about $19 million in Delaware, $83 million in Maryland, $71 million in New York, $378 million in Pennsylvania, $307 million in Virginia, and $44 million in West Virginia. Alternative watering (11%), livestock waste management systems (26%), and stream access control (21%) again account for the majority (58%) of total annual costs across the entire watershed. These high-cost practices prove less cost-effective than many others in the cost-effective BMP portfolios discussed below.

Cost-Effective BMP Portfolios. Significant cost savings can result from implementation mechanisms that encourage selection of BMPs and spatial targeting according to cost-effectiveness, as compared to the costs of installing the BMPs associated with the state WIPs (Table 3). Scenario 1 (no land retirement) results in Bay-wide cost savings of 22% as compared to total annual WIP costs, although this figure must be qualified because reductions from available BMPs in scenario one do not reach TMDL load reduction targets for Pennsylvania and Virginia. These shortfalls are due to the exclusion of land retirement practices in scenario 1 as well as data limitations that prevent the inclusion in our analyses of interim BMPs such as manure technology in Pennsylvania. By contrast, the WIPs include and claim nutrient reductions for these interim BMPs. In scenario 2 (25% land retirement), Bay-wide cost savings increase to 60%. Among jurisdictions, cost-savings relative to the WIPs in scenario two range from 27% (Virginia) to 86% (New York and West Virginia). All TMDL load reduction targets are met in scenario 2. There was a lack of significant spatial heterogeneity in the cost data within jurisdictions as the USEPA/Abt cost data generally estimated one cost for each jurisdiction. As a result, the spatial targeting of BMPs is largely influenced by delivery factors, with implementation tending to increase in those land-river segments with higher delivery factors.

The fact that reductions from available BMPs in scenario one do not reach TMDL load reduction targets for Pennsylvania and Virginia means that all practices in these states, even prohibitively expensive ones, are required in order to get as

Table 4. Five Highest-Cost BMPs for each Jurisdiction: WIPs vs. Cost-Effective BMP Portfolios

	WIPs		Scenario 1		Scenario 2	
	BMP	annual cost ($ million)	BMP	annual cost ($ million)	BMP	annual cost ($ million)
Delaware	decision agriculture	$5.2	water control structures	$2.3	water control structures	$1.9
	AWMS - poultry	$3.1	AWMS - poultry	$1.0	land retirement	$$1.1
	manure transport outside CBWS	$2.6	conservation plans	$0.3	conservation plans	$0.2
	AWMS - livestock	$2.3	capture and reuse	$0.2	capture and reuse	$0.2
	wetland restoration	$1.8	barnyard runoff control	$0.1	barnyard runoff control	$0.1
Maryland	AWMS - livestock	$27.7	water control structures	$10.2	land retirement	$6.0
	decision agriculture	$18.4	cover crops	$1.3	water control structures	$5.6
	liquid/poultry manure injection	$11.3	capture and reuse	$0.7	capture and reuse	$0.6
	cover crops	$10.3	conservation plans	$0.6	conservation plans	$0.3
	capture & reuse	$2.8	nutrient management	$0.1	cover crops	$0.3
New York	stream access control w/ fencing	$24.8	stream access control	$24.5	land retirement	$6.7
	alternative watering	$15.6	AWMS - livestock	$8.3	cover crops	$1.7
	liquid/poultry manure injection	$9.0	ammonia emissions reduction biofilters	$6.6	conservation plans	$0.7
	wetland restoration	$3.8	cover crops	$4.0	capture and reuse	$0.6
	AWMS − livestock	$3.4	enhanced nutrient management	$2.5	nutrient management	$0.2
Pennsylvania	AWMS - livestock	$105.0	AWMS - livestock	$97.8	land retirement	$39.7
	alternative watering	$85.2	ammonia emissions reduction biofilters	$44.7	cover crops	$21.0
	stream access control w/ fencing	$29.0	stream access control	$43.2	ammonia emissions reduction biofilters	$17.6
	precision intensive rotational grazing	$26.3	cover crops	$28.1	capture and reuse	$8.9
	forest buffers	$23.2	capture and reuse	$9.5	prescribed grazing	$4.0
Virginia	AWMS − livestock	$96.2	stream access control	$121.6	land retirement	$76.3
	stream access control w/ fencing	$94.2	AWMS - livestock	$108.2	AWMS - Livestock	$68.4
	mortality composters	$22.7	ammonia emissions reduction biofilters	$40.0	prescribed grazing	$19.5
	cover crops	$19.1	cover crops	$34.3	cover crops	$16.2
	tree planting	$9.2	prescribed grazing	$26.1	nutrient management	$15.6
West Virginia	stream access control w/ fencing	$37.1	stream access control	$15.3	land retirement	$3.1
	AWMS − poultry	$2.0	prescribed grazing	$1.0	stream access control	$2.0
	AWMS − livestock	$1.8	barnyard runoff control	$0.2	prescribed grazing	$0.7
	mortality composters	$0.8	enhanced nutrient management	$0.1	barnyard runoff control	$0.2
	nutrient management	$0.7	conservation plans	$0.1	conservation plans	$0.1

close as possible to TMDL load reduction targets. In Pennsylvania, estimated load reductions meet approximately 72% of the state's N target, 98% of its P target, and 97% of its TSS target. In Virginia, the N load reduction target is met, but estimated load reductions meet only about 62% of the state's P target and 94% of its TSS target. Costs of fully implementing all available BMPs are less than the cost of the WIP in Pennsylvania but greater than the cost of the WIP in Virginia.

Scenario two converts up to 25% of applicable acres in each land-river segment to either hay without nutrients or forest. This has the effect of reducing the available acres for scenario one BMPs by 25% for those acres retired. Land retirement practices are relatively cost-efficient in comparison to some BMPs that involve keeping land in production. Conversion to hay without nutrients is more cost-effective for reducing nutrient loads in every state except Virginia. In Virginia, conversion of land to forest is necessary in order to achieve its TSS load reduction target specified in the TMDL. Including land retirement as an option increases the load reductions for all three pollutants in each jurisdiction. All TMDL load reduction targets are met in scenario two, with large cost savings in every jurisdiction as compared to WIP costs.

Table 4 details and compares the five highest-cost BMPs for each jurisdiction for the WIPs, scenario one, and scenario two. The SI presents a full breakdown of annual costs by jurisdiction and BMP for scenario one (SI Table S2) and scenario two (SI

Table S3). There are significant differences in the mix of BMPs between the WIPs and the cost-effective portfolios. In general, capital-intensive practices involving new structures or equipment contribute more prominently in the WIPs than in the cost-effective portfolios, while management-intensive practices involving changes in the use of existing farm resources constitute the majority of expenses in the cost-effective portfolios.

Animal waste management systems (livestock) are a major part of the WIPs for all six jurisdictions, but drop completely out of the cost-effective portfolios in scenario two for all states except Virginia. Stream access control with fencing is a significant expenditure in the WIPs for New York, Pennsylvania, Virginia, and West Virginia, but in the cost-effective portfolios for scenario 2 it is only a major expenditure for Virginia. Animal waste management systems (poultry) form part of the WIPs for all six jurisdictions, but in the scenario 2 cost-effective portfolios they are only important in Virginia (they are also used to a very small extent in Pennsylvania). In the scenario 2 cost-effective portfolios, the single-largest expenditure in every jurisdiction except Delaware is land retirement (it is the second-largest in Delaware), whereas land retirement is relatively unimportant in the WIPs. Other BMPs that feature prominently in the cost-effective portfolios compared to the WIPs include cover crops, prescribed grazing, and nutrient management.

■ DISCUSSION

The cost of implementing the agricultural BMPs required by the Chesapeake Bay Watershed Implementation Plans (WIPs) between 2011 and 2025 is about $3.6 billion (in 2010 dollars). The annual cost associated with full implementation of all WIP BMPs from 2025 onward is about $900 million. Our results show that significant cost savings can be realized through more judicial BMP selection and spatial targeting that take into account the relative cost-effectiveness of alternative BMP types and locations. When retiring up to 25% of current agricultural land is included in the list of options (scenario two), Bay-wide cost savings are about 60% compared to the WIPs. Among the states in the Bay Watershed, cost-savings relative to the WIPs in this scenario range from 27% (Virginia) to 86% (New York and West Virginia).

Van Houtven et al. examine the potential for nitrogen and phosphorus credit trading in the Chesapeake Bay region, including trading between point and agricultural nonpoint pollution sources.[11] Their results can be compared with ours insofar as the MAC for agriculture for a pollutant can be viewed as tracing out a supply curve for credits potentially available for sale from farms to point sources. Depending on how a credit trading program was designed, farms might have to take certain actions or meet certain pollution reduction targets before they could begin selling credits to point sources. Van Houtven et al. find that cover crops and grass buffers are the two most important BMPs used for trading credits with point sources (as measured by credit trading expenditures).[11] In scenario two of the present study, the two most important BMPs for the Bay region as a whole (as measured by costs) are land retirement and cover crops, with grass buffers not being used at all. Van Houtven et al. use the same watershed model (CBWM Phase 5.3.2) as our study, so the differing results may be due to differences in cost estimates for various BMPs.

Hanson and McConnell examine potential nitrogen credit trading in Maryland between sewage treatment plants and farms adopting cover crops.[12] They find that nitrogen trading could significantly reduce the cost of achieving water quality goals for nitrogen but could worsen phosphorus pollution since point-source reductions in phosphorus would be lost and cover crops do little to reduce phosphorus runoff. This highlights the importance of achieving load reductions goals for multiple pollutants simultaneously. In scenario 2 of our results, nitrogen is the "binding" pollutant in Delaware, Maryland, Pennsylvania, and Virginia, that is, meeting the TMDL goal for nitrogen requires adopting additional BMPs beyond those needed to meet the TMDL goals for phosphorus and sediment. In New York, phosphorus is the binding pollutant, while sediment is the binding pollutant in West Virginia.

The potential for significant cost-savings from efficient BMP selection and targeting is important for watershed planning and resource allocation intended to achieve water quality goals without undue economic harm. It can be viewed as a positive message for farmers and state and federal governments given the historical reliance on technical and financial assistance, mainly from USDA conservation programs but also from state agencies, to fund BMP implementation. For spending meant to clean up the Chesapeake Bay, the impacts of these increasingly scarce resources can be maximized by prioritizing BMPs and locations according to cost-effectiveness in reducing pollution loads in the Bay.[13,14]

The results of this study must be qualified because they focus on pollutant deliveries to the Chesapeake Bay and do not consider other potential advantages of BMPs, such as non-water quality related benefits and local water quality benefits in areas immediate to where they are installed. Other studies serve as models as to how these benefits could be incorporated in future research.[15,16] The results here must also be qualified by the fact that they assume that the baseline BMP adoption Figures (2009 or 2011) accurately reflect the BMPs that are actually in place as of that year, and that BMPs to be adopted by 2025 will in fact be implemented and maintained. These assumptions are questionable as studies have indicated that current tracking methods tend to overstate BMP implementation and maintenance,[17] although this is a limitation of not only our study but also every study using similar data.

The land use scenario approach used here has the advantages of being straightforward and insightful, but it does not indicate what the economically efficient amount of land retirement might be. The economics of agricultural land use in the region generally, and as affected by the Bay TMDL, are complex.[18] For example, continued conversion of agricultural land to urban uses could mean that some farmland slated for BMP adoption in the analyses here may no longer be in agriculture in 2025. Other considerations may also come into play, including concerns that large-scale land retirement could lead to loss of income and employment for local businesses upstream and downstream of farms in the agricultural supply chain.

Two other caveats on our results are in order. First, we do not consider the transaction costs of implementing and maintaining BMPs (e.g., time spent by farmers on paperwork and reporting requirements or meetings with government personnel). Doing so would increase the estimated costs of the WIPs and both scenarios. Further research is need to determine if transaction costs differ significantly from one type of BMP to another, which could affect the cost-effective mix of BMPs. Second, neither our land retirement scenario nor the CBWM addresses the question of what happens to manure that had been applied to land that is converted to either hay without nutrients or to forest. If this "leftover" manure were applied to remaining cropland, the cost-effectiveness of land retirement would be reduced. Implicitly, the land retirement scenario and the CBWM assume that livestock numbers fall by an amount sufficient to eliminate this leftover manure. Further research is needed to examine the impacts of large-scale land retirement on herd sizes and manure application practices.

ASSOCIATED CONTENT

Supporting Information

A map of land-river segments in the Chesapeake Bay Watershed, definitions of the BMPs, and tables with additional results are available. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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