Why Metrics Matter: Evaluating Policy Choices for Reactive Nitrogen in the Chesapeake Bay Watershed[†]

MELISSA B. L. BIRCH,[‡]
BENJAMIN M. GRAMIG,[§]
WILLIAM R. MOOMAW,[*,‡]
OTTO C. DOERING, III,[§] AND
CARSON J. REELING[§]

Center for International Environment and Resource Policy, The Fletcher School, Tufts University Medford, Massachusetts 02155, and Department of Agricultural Economics, Purdue University, West Lafayette, Indiana 46202

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Despite major efforts, the reduction of reactive nitrogen (Nr) using traditional metrics and policy tools for the Chesapeake Bay has slowed in recent years. In this article, we apply the concept of the Nitrogen Cascade to the chemically dynamic nature and multiple sources of Nr to examine the temporal and spatial movement of different forms of Nr through multiple ecosystems and media. We also demonstrate the benefit of using more than the traditional mass fluxes to set criteria for action. The use of multiple metrics provides additional information about where the most effective intervention point might be. Utilizing damage costs or mortality metrics demonstrates that even though the mass fluxes to the atmosphere are lower than direct releases to terrestrial and aquatic ecosystems, total damage costs to *all* ecosystems and health are higher because of the cascade of Nr and the associated damages, and because they exact a higher human health cost. Abatement costs for reducing Nr releases into the air are also lower. These findings have major implications for the use of multiple metrics and the additional benefits of expanding the scope of concern beyond the Bay itself and support improved coordination between the Clean Air and Clean Water Acts while restoring the Chesapeake Bay.

Introduction

It is often said that we cannot manage what we do not measure. One compelling reason for the interest in metrics related to pollutants is the role they play now and in future regulation. Current pollutant regulation utilizes a single metric in determining standards, compliance, and performance. The metrics used may be more or less accurate or technically sound, and become the policy standard. The tendency has been to use physical measures rather than metrics such as economic damages or societal preferences. However, the latter two are increasingly of interest.

In recent years, measurement in the pursuit of effective environmental management has become increasingly sophisticated and linked to both monitoring and computer modeling. The monitoring systems and suite of models used to simulate nutrient movement, water quality, and living resources in the Chesapeake Bay have been used to determine the nutrient caps agreed to by the watershed states (*1*).

It is also the case, however, that what is measured may determine what is managed and how it is managed, making it essential that the metrics used for defining and managing environmental problems are carefully chosen. In this paper, we demonstrate that multiple metrics may be required to provide appropriate information on the flow of chemical species through ecosystems and the diverse impacts of those flows in individual ecosystems and on human health. The many interactions of the biogeochemical and social systems require that the complexity of the policy solution be commensurate with the complexity of the problem (*2*). Taking such an integrated look at environmental complexities is as intellectually challenging as it is necessary, because decisions have to be made and actions have to be taken on an ongoing basis. In this paper, we strive to develop a comprehensive scientific basis for policy while acknowledging and accepting the uncertainties and limitations inherent in such an applied analysis. The use of a single or too few metrics produces policy responses that oversimplify environmental problems and actual ecological systems, resulting in unanticipated adverse "side effects" and regulatory and economic inefficiencies. This problem is demonstrated by the separate and uncoordinated policy response of the regulatory-based Clean Air and Clean Water Acts and the production-oriented farm bills. These involve, for the most part, single metric approaches that can result in missed opportunities for more cost-effective control—depending upon the regulatory goal. (For discussion of Clean Water Act/Farm Bill trade-offs see ref *3*.)

Our analysis will focus on the Chesapeake Bay watershed, but will address not only the water quality of the Bay, but all damage from Nr and media within the watershed. Traditionally, the nitrogen cycle is described in terms of tonnes (or lbs) of nitrogen, or in terms of pollutant releases and/or concentrations in water or air. We will examine tonnes of nitrogen as one metric in combination with other metrics that may be used to describe the cascade of reactive nitrogen (Nr) through ecosystems, including damage costs, human mortality and morbidity, and mitigation costs.

Cascading Reactive Nitrogen and Its Regulation

Reactive nitrogen (Nr) is any chemical form of nitrogen that is readily converted into another chemical species. It includes all chemical forms of nitrogen other than N_2. In recent years, the analysis of the movement of nitrogen as a simple nitrogen cycle has been replaced with a more comprehensive nitrogen cascade in which nitrogen changes chemical form as it moves through multiple media and ecosystems (*4*). The nitrogen cascade provides a more accurate accounting of the mobility, forms, and consequences of Nr released into the environment.

When Nr is released into the environment, it can follow a variety of paths through ecosystems, changing chemical form, and causing damage at multiple points. For instance, while some Nr emitted as NO_x may be denitrified in the atmosphere, thus ending their "cascade," others could first react to form ozone (O_3), then particulate matter (PM), then be deposited in a forest as acid deposition, then leach into a stream, and finally be conveyed to an estuary to contribute to anoxia before being stored in sediments or denitrified (*5*). In the case of the Chesapeake Bay, the cascade comprises

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* Corresponding author phone: 1-617-627-2732; fax 1-617-627-3005; e-mail: william.moomaw@tufts.edu.
[‡] Tufts University.
[§] Purdue University.

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not just the Bay and its tributaries, but also the entire watershed and the airshed from which anthropogenic additions of nitrogen to the Bay may originate.

Anthropogenic flows of Nr are regulated under two major pieces of legislation: the Clean Air Act and the Clean Water Act. Under the Clean Air Act, the EPA is required to set and periodically review primary (health-related) and secondary (welfare-related) National Ambient Air Quality Standards (NAAQS) for criteria pollutants. Among the pollutants covered by NAAQS are three related to the nitrogen cascade: NO_2, particulate matter, and ozone. It is useful to note that while many monetary and nonmonetary metrics are used for evaluating and justifying possible air regulations, and others are used for implementing them, only a single metric is the basis for an actual standard: the concentration of the particular pollutant in the air during a specified time period (*6*).

Under the Clean Water Act (*7*), the Chesapeake Bay has been the subject of multiple agreements among watershed states and the EPA, beginning in 1983 and culminating with the Chesapeake 2000 Agreement. The Chesapeake 2000 Agreement states that “We have agreed to the goal of improving water quality in the Bay and its tributaries so that these waters may be removed from the impaired waters list...” (*8*). This agreement sets out a variety of metrics by which the Bay’s recovery is to be judged. These metrics are focused only on the goal of improving the water quality of the Bay, and do not address the complexity of the biogeochemical system within which the Bay is embedded or other possible actions that may yield benefits beyond water quality alone.

The Chemical Nitrogen Cascade

We analyze Nr in the Chesapeake Bay watershed with a chemical cascade showing the amount of Nr from each source type cascading through the different media. The following flow estimates are based upon the Chesapeake Bay Program’s (CBP) suite of models. The scenario used by the CBP for the estimates used here is the “s65prog08b” scenario, which estimates Nr and other flows for 2008, assuming hydrologic and climatic conditions based on an average from 1985 to 1994. Estimates of atmospheric deposition are the product of the airshed model used by the CBP (the Regional Acid Deposition Model, RADM). These are then fed into the watershed and estuarine models (*9*).

NO_x and NH_3 emissions for the Chesapeake Bay watershed are estimated by summing the county level emissions for the watershed from the EPA’s National Emissions Inventory (NEI) (*10*). The 2005 NEI data released in 2008 are the most recent data available from EPA. We assume that 2008 watershed emissions are equal to 2005 emissions for the purposes of this analysis. N_2O emissions (from fertilizer only) are estimated using the ratio of the Chesapeake watershed N fertilizer to national N fertilizer, and assuming that the rate of N_2O emissions from fertilizer within the Chesapeake watershed is the same as the average rate for the country (*11*−*13*).

Figure 1 diagrams the principal flows in the Chemical Nitrogen Cascade for the Chesapeake basin. The cascade shows the amount of Nr from each source cascading through each medium. Arrow color indicates whether fluxes originated as anthropogenic additions to the atmosphere, to terrestrial ecosystems, or to freshwater ecosystems. All fluxes are in annual metric tonnes N. Approximately 24% of Nr reaching the bay originated in emissions to the atmosphere, 57% came from terrestrial additions, and the remaining 19% came from direct releases to freshwater ecosystems. These estimates include atmospheric deposition to freshwater and to the bay, which are 2028 and 9072 tonnes, respectively. These fluxes are omitted from the diagram due to their relatively small size (*10, 11, 14*).

While the chemical nitrogen cascade is essential to our understanding of the Bay system, it is only one of the potential metrics that can be used to evaluate the impacts of Nr fluxes. The cascade demonstrates the sequence in which different forms of Nr appear, and assists in identifying different chemical forms of Nr in different media that have adverse health and environmental consequences beyond those of water quality in the Bay. An alternative basis for examining Nr fluxes is to identify the damage caused by each chemical form of Nr, and to express the damage costs in the common metric of dollars. Translating Nr fluxes into economic values is achieved using previous studies that have been published in the scientific literature or have been accepted for use in EPA Regulatory Impact Assessments to quantify the economic value of avoiding adverse health outcomes or reducing mortality risks, the willingness to pay for improvements in environmental quality, or the willingness to accept payment for foregoing an improvement in environmental quality.

Economic Damages and the Economic Nitrogen Cascade

Economic damages occur from the release of Nr directly into water bodies from agricultural runoff, livestock, and sewage treatment plants mostly in the form of nitrate. Addressing these releases has been the major focus of attempts to restore the Chesapeake Bay. Additional Nr is applied to the land as fertilizer, and eventually makes its way into fresh water and estuaries. Emissions of NO_x from combustion and industrial processes produce ozone, particulates, and acid rain and eventually release nitrate into the Bay. While a tonne of Nr as nitrate is the same regardless of how it is delivered to the Bay, the extra damage that occurs from air emissions prior to reaching the Bay is substantial as will be demonstrated below. Ammonia is another airborne source of Nr that can produce particulates and other impacts on ecosystems. We have identified as many of these Nr releases as we could find and used data on the economic damage costs of each type of release to create an Economic Nitrogen Cascade that attaches economic damage costs to each step in the chemical cascade for which estimates are available. While the land and direct water releases are quite straightforward, the air emissions require major modeling to obtain the full range of impacts, as airborne releases are chemically transformed and cascade through several media and ecosystems.

Whereas chemical N flows affect ecosystems in many different ways that may impact human welfare, estimating the benefits of all of these impacts requires multiple studies or tools. We utilize damage and abatement costs from existing studies to evaluate the benefits from reducing chemical N flows to the land and water for the other values in the economic cascade, as detailed in the accompanying Supporting Information (SI).

Weather patterns and the geographic location of emissions sources determine the effect of NO_x emissions on ambient air quality at individual locations at different points in time. Air emissions within the Chesapeake Bay (*10*) serve as an input to air quality models used to determine source−receptor coefficients (SRCs) that map NO_x emissions to localized ambient concentrations for $PM_{2.5}$ and ozone based on the Urban-to-Regional Multiscale-One Atmosphere model (URM-1 ATM) that has been used extensively for air quality modeling in the literature (*15*−*20*). We have only considered Nr originating within the watershed even though airborne forms of Nr come from a larger airshed affecting many more people. The EPA’s BenMAP software program was used to estimate the associated change in the incidence of morbidity and mortality and the economic damage (benefit) from continued (eliminated) chemical Nr flows associated with NO_x (*21*). A detailed account of how emissions data, SRCs, and BenMAP are used to estimate the economic damages reported can be found in the SI.

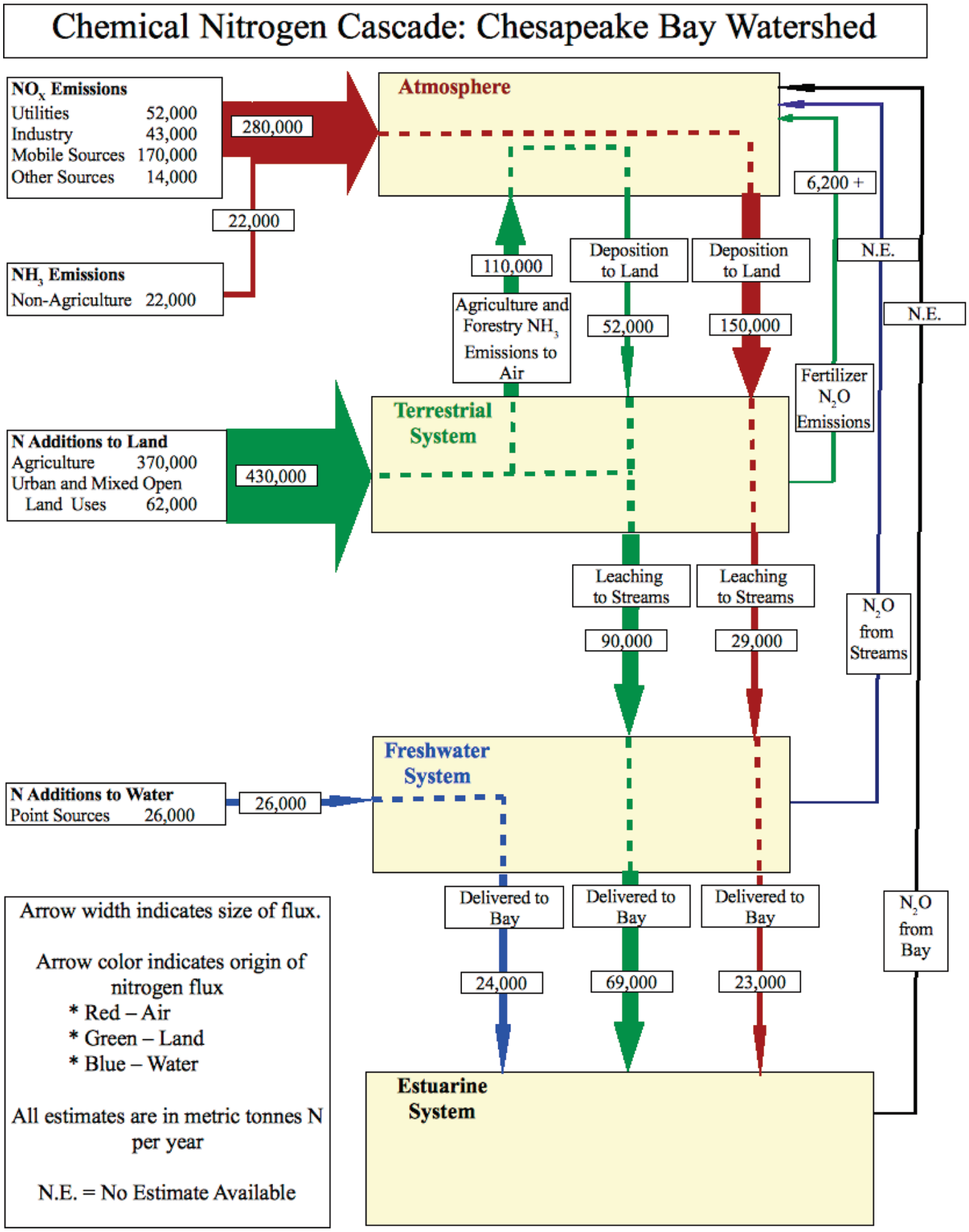

FIGURE 1. Chemical Nitrogen Cascade in the Chesapeake Bay Watershed (tonnes/year). See SI for sources and calculations.

TABLE 1. Avoided Incidences of Health Outcomes and Economic Benefits from the Elimination of Livestock Ammonia and NO_x Precursors to Ozone (O_3) and $PM_{2.5}$ from Designated Sources in the Chesapeake Bay Watershed (Dollars in Year 2000)

	mortality effects avoided damages ($million) (change in incidence)			morbidity effects avoided damages ($million) (change in incidence)		
pollutant	livestock ammonia	mobile sources	large stationary sources	mobile sources	large stationary sources	economic damage per tonne N
ozone	N/A	$1,485 (235)	$659 (104)	$66 (521,913)	$29 (234,648)	$8,513
$PM_{2.5}$	$1,691 (292)	$2,584 (409)	$1,071 (169)	$108 (203,947)	$67 (84,026)	$14,556

The results of the analysis of morbidity and mortality effects from all causes and the health outcomes caused by NO_x emissions from large stationary sources (includes electric utilities and large industrial sources) and mobile sources in the Chesapeake Bay airshed are contained in Table 1.

The results of the analysis of health effects from baseline $PM_{2.5}$ and O_3 concentrations in the Chesapeake air- and watershed are indicative of the general result that reduced mortality from air quality improvements tend to be the single largest source of benefits to be taken into account when evaluating the costs and benefits of improving environmental quality. The estimated benefits from reduced mortality alone represent 96% of the total health benefits (inclusive of all morbidity effects) from the elimination of all large stationary and mobile source NO_x precursors to $PM_{2.5}$. The economic damage generated by $PM_{2.5}$ per tonne of Nr emitted as NO_x by these sources is $14,556. The economic damages generated by O_3 per tonne of Nr emitted as NO_x by all large stationary and mobile sources is $8,513. Since protecting human health is a primary goal of the Clean Air Act, coordinating air quality improvement with water quality restoration in the Bay provides additional support for achieving the latter goal.

Inherent nonlinearities in concentration−response relationships for O_3 mean that linear extrapolation of the SRCs over the entire range of NO_x emissions underestimates the expected ozone response to emissions reductions. Because we assume linearity in our analysis, the estimated benefits from eliminating NO_x flows we report are considered conservative for the health end points included in our analysis (*15, 22, 23*).

Damages caused by ammonia (NH_3) emissions from livestock were also quantified. National per-head damage figures for emissions from cattle, hogs, and poultry were derived from ref *24*. These per-head figures were then scaled to the number of cattle, hogs, and poultry in the watershed to approximate the economic damages from mortality caused by livestock. Further details can be found in the SI.

It is important to note that our study is limited by the availability of existing valuation studies that quantify economic damages. No such studies were available for ozone depletion, greenhouse gas impacts, fertilization benefits, and materials damage from atmospheric N deposition, freshwater recreational fishing, commercial fishing, and ecosystem services throughout the cascade. This is important because it illustrates the point raised at the outset that "we cannot manage what we do not measure." Another way of looking at this is that if we do not have a measure of economic benefits or damages associated with a particular chemical flow then we cannot effectively use economic damages to compare it with another chemical flow in setting policy priorities or evaluating the efficiency of public investments in environmental quality.

Figure 2 shows an Economic Nitrogen Cascade for the Chesapeake Bay watershed. Based upon earlier work by Moomaw and Birch, total damage costs are the result of multiplying total annual per tonne damage costs (in the yellow boxes) by the chemical flows (*25*) (detailed calculations can be found in the SI). As can be seen by these figures, damage costs from air emissions are substantially larger than those from other source categories (despite being smaller fluxes). This is due primarily to the dominance of estimated damages to human health, most significantly mortality benefits from reduced $PM_{2.5}$. Nr from air emissions also cascades through multiple media and ecosystems, and the damage costs cascade as well. The large difference in the relative damage costs and chemical fluxes in the two cascade diagrams demonstrates the importance of using multiple metrics in selecting what to regulate and when and where to regulate it.

The economic cascade also demonstrates the opportunities to meet multiple health and environmental goals while improving the water quality in the Bay. Releases of Nr to different points in the N cascade affect human morbidity and mortality outcomes in different ways. Morbidity effects are measured by the change in the number of expected cases of an illness attributable to the chemical Nr flow from a particular source and mortality effects are measured by the number of expected deaths attributable to the same chemical flow.

To evaluate policy interventions at different points in the N Cascade using economic metrics, it is necessary to consider not only the avoided damages associated with different chemical flows, but also the abatement cost associated with reducing or eliminating different sources of Nr in the Chesapeake Bay system.

Annual abatement costs per tonne of Nr listed in Table 2 are adjusted for inflation using the Consumer Price Index. These abatement costs reflect the marginal cost of abatement, based on the current or most recent abatement cost figure available in the peer-reviewed literature.

Abatement costs differ across sources but realistically also depend upon current concentration levels because initial reductions are expected to cost significantly less per unit than the cost of removing the last several units of Nr from a given source category. Past efforts to reduce Nr from particular source categories are likely to contribute to heterogeneity in abatement costs when the full range of Nr abatement options is taken into account.

Comparing Metrics for Integrated Management

Our four metrics can be compared to each other as shown in Figure 3, which shows the current share of each medium's (air, terrestrial, and freshwater) contribution to Nr fluxes to the Chesapeake Bay system. These estimates are based on the cascading costs methodology and data in Moomaw and Birch, in which costs (or mortality rates) are scaled by the amount of Nr from a particular source reaching terrestrial, aquatic, or estuarine ecosystems (*29*). The scaled estimates are then aggregated to provide an estimate of the total damage costs (or mortality) associated with each source type.

According to these estimates (which omit the 14,000 tonnes of NO_x emissions from "Other Sources" due to lack of economic estimates), freshwater releases—the second most expensive to mitigate—account for the smallest portion of Nr contributions to the system by any of the metrics considered: only 4% of the Nr, 2% of the cost damages, and none of the mortality losses. Additions of Nr to terrestrial ecosystems add 60% to the system, but contribute only 24% of the damage costs and 24% of the mortality, with the highest mitigation costs. Atmospheric emissions account for 37% of Nr entering the watershed, but they account for 75% of the dollar damages and 76% of the mortality. Mitigation costs per tonne are the lowest among the three sources.

Differing damage costs arise from the cascade of atmospheric emissions through more parts of the Bay system. By using several different metrics, particular attention is drawn to the potential for gains from reducing different Nr sources—atmospheric, terrestrial, and freshwater emissions—and assisting in setting priorities. Thus the reduction of damages from Nr (including freshwater and estuarine impacts) may benefit as much from a stricter control of air pollution as from stricter water pollution controls. This challenges our traditional approach to regulation in terms of single media and goals, but environmental management decisions could become more effective and economically efficient by the use of a suite of common unit metrics. This point is underscored by Figure 4, which shows total quantified damage costs from different sources relative to their respective chemical flows. Metrics can thus be used as a tool to integrate policymaking across environmental media throughout the cascade.

Note that direct additions to the environment from agriculture are about 370,000 tonnes Nr/year, and cause $1.7 billion worth of damage. Emissions of NO_x from mobile sources represent only 180,000 tonnes Nr/year, but cause nearly $4.4 billion in damages each year, of which $108 million is attributable to nitrate loading of the Chesapeake Bay, $3.9 billion to human morbidity and mortality, and the remainder to other

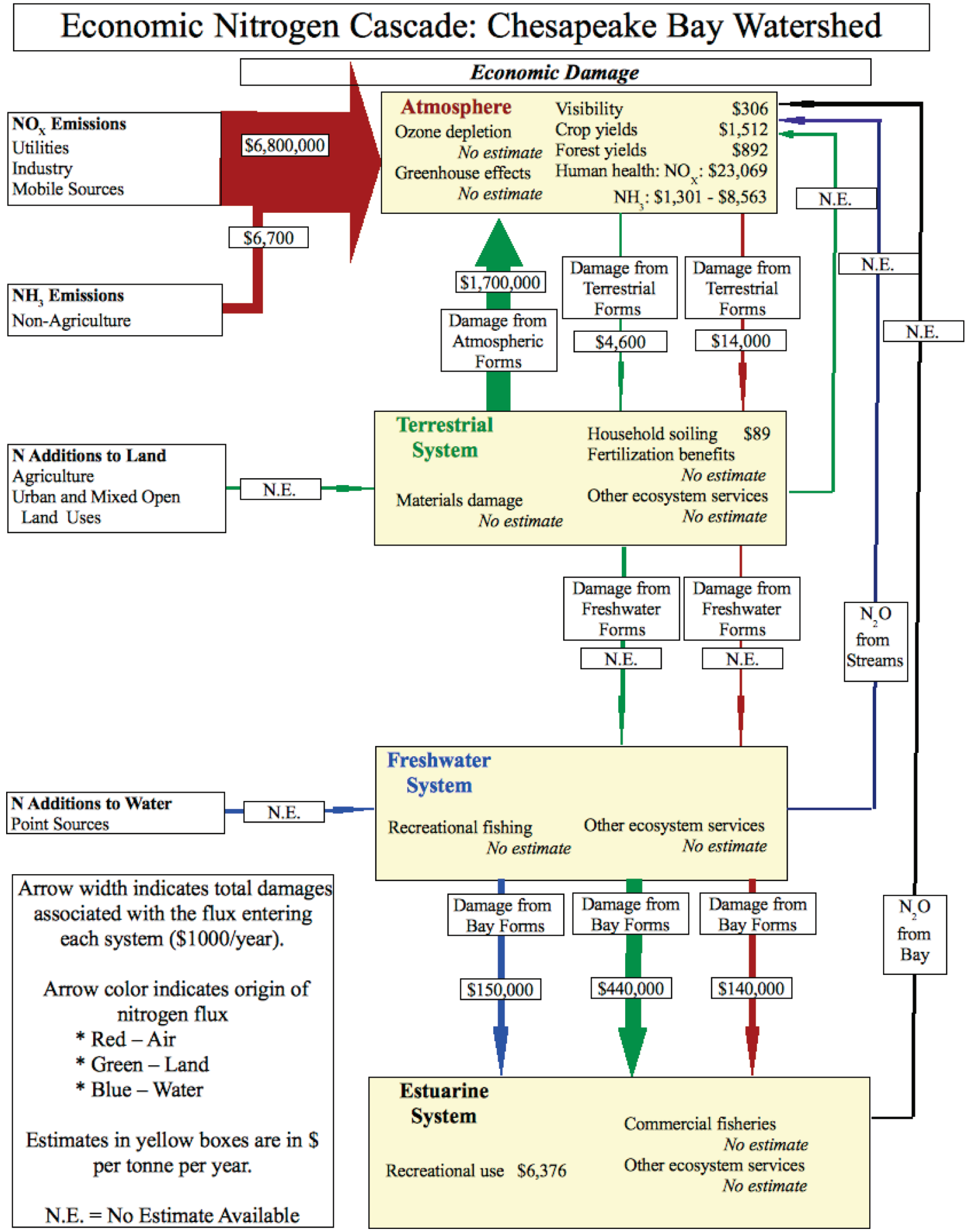

FIGURE 2. Economic Damage Cascade. See SI for sources and calculations.

forms of damage, such as crop and commercial forest damage. Hence the releases of Nr into the air from mobile sources, which are only half the amount of agricultural releases, cause more than 2.5 times the economic damage of environmental additions from agricultural ecosystems. This integrated inclusion of atmospheric, terrestrial, and aquatic additions of Nr is not reflected in today's regulations. The NO$_x$ SIP Call Regulatory Impact Assessment and associated State budgets consider controls only for major stationary sources of NO$_x$. The Clean Water Act, in Section 208, provides for area-wide treatment planning that does not explicitly include atmospheric sources. In the case of the Chesapeake Bay Program, the process of setting and allocating nutrient caps only considered reductions of atmospheric loads resulting from national NO$_x$ regulations. However, further mandatory atmospheric reductions are not considered in the tiered nutrient reductions in the technical

TABLE 2. Marginal Abatement Cost per Tonne of Nr by Source ($ US 2000)

location in the N cascade where emitted	source/pollutant	abatement cost per tonne of Nr
air	electric utilities/NO_x (*26*)	$4,800
	industrial/NO_x (*27*)	$22,000
	mobile sources/NO_x (*28*)	$14,000
	non-agricultural/NH_3	no estimate
land	agriculture/nitrate (*29*)	$10,000
	urban and mixed open land uses/nitrate (*29*)	$96,000
freshwater	point sources/nitrates (*29*)	$18,000

assessments associated with the implementation of the Chesapeake 2000 Agreement.

To expand the range of policy and technological options considered, it is useful to apply multiple metrics at the start of the process to identify effective intervention points throughout the cascade and determine which sources should be targeted for reductions. In other words, rather than determining that reductions will be made to a particular category of sources or chemical species and then applying economic and ecological metrics to just a single category, the economic, health, and ecological metrics should be applied to the entire range of sources and affected ecosystems. Then policy options may be selected based on this analysis. Similarly, it would be quite useful to include in the metrics ancillary or cobenefits, which would facilitate the consideration of solutions that more efficiently address multiple problems simultaneously, such as NO_x-reduction and climate change (*30*).

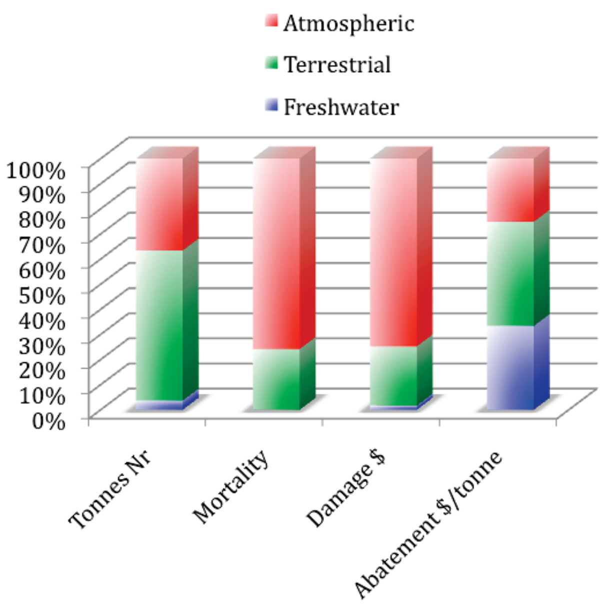

FIGURE 3. Share of contributions from all reactive nitrogen sources in the Chesapeake Bay watershed according to different metrics.

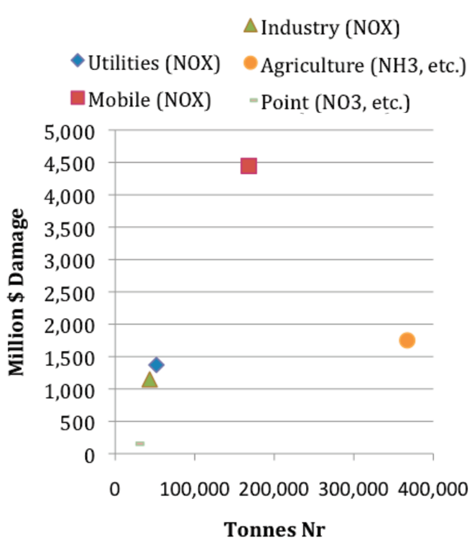

FIGURE 4. Quantified damage costs (including health impacts) relative to tonnes of reactive nitrogen.

We have focused thus far on four major metrics: tonnes Nr, mortality, damage costs, and abatement costs. As we have demonstrated, using these metrics in combination identifies a more efficient use of abatement funding and avoids trade-offs that the public would likely find undesirable (such as a failure to minimize mortality, for instance). Finding multiple benefits may even build additional public and political support for goals such as restoring water quality in Chesapeake Bay.

Nevertheless, such metrics often have "missing" components—all damages are monetized. In some cases, this can be remedied through additional research. However, certain ecosystem services such as biodiversity cannot be monetized, or otherwise reflected in any of the four metrics. It is therefore useful also to utilize a more comprehensive set of qualitative metrics that reflects the loss of ecosystem services that are damaged by anthropogenic overloading of the nitrogen cycle. While there is some basis for this in environmental law and recent EPA practice, a more systematic approach would yield substantial environmental, human health, and economic benefits.

The inclusion of measures of cobenefits and ecosystem services is likely to have a significant effect on the type of solutions chosen to meet Nr reduction goals. Including them requires more fundamental changes to energy and agricultural production systems, in contrast to end-of-pipe and edge-of-field solutions that represent the current approach pursued in the Chesapeake Bay watershed.

Throughout this report, we have sought to demonstrate how multiple metrics can inform analysis of policy alternatives, providing a more solid basis for the choices ultimately made. Our analysis shows that prioritizing damage costs and health and mortality metrics can lead to different policy choices relating to the environmental medium and emissions sources that are chosen for reductions, with a greater emphasis on atmospheric emissions. Utilizing the Chemical and Economic Nitrogen Cascades identifies forms of Nr that cascade through more media and ecosystems causing more economic damage than direct release of Nr into the Bay. Understanding the temporal sequence of the cascade allows environmental managers to identify the furthest point upstream in the cascade, and take action there to avoid the many downstream impacts.

Such considerations are largely absent from current air and water pollution laws and regulations and are not part of the decision of how to allocate federal pollution control resources. The production goals of farm bills also compete with reductions in Nr. The Clean Air Act focus on individual pollutants fails to capture the complexity of the multiple impacts of those pollutants and their transformation across media. In the case of the Chesapeake Bay program, several metrics are used for judging progress on the rehabilitation of the Bay itself, there is no consideration of ancillary benefits to human health or well-being and non-Bay ecosystem services.

Again, while the Chesapeake Bay Program's efforts to model the transport of nutrients and other pollutants through the different ecosystems in the watershed should be lauded, the unique focus on metrics relating to the Bay water quality results in a missed opportunity to prioritize actions that could have multiple benefits including health throughout the entire chemical cascade and a much broader geographical area. This paper is not advocating abandoning addressing non-point source pollution from agriculture. Rather the intent is to inform the public and policy makers of the opportunity costs and trade-offs among different approaches in a multimedia/multimetric framework in order to make cost-effective decisions that reflect societal priorities. Introducing multiple metrics would produce greater reductions in Nr from sources that have been the most responsible for the degraded quality of the Bay's waters, and would spread abatement costs among multiple additional polluters. By simultaneously addressing multiple damages to human health and other environmental issues, additional reductions in Nr into the Bay can be achieved as well. These findings have major implications for the use of multiple metrics and the additional benefits of expanding the scope of concern beyond the Bay itself and demonstrate how improved coordination between the Clean Air and Clean Water Acts can accelerate the restoration of the Chesapeake Bay, and reduce total mitigation costs.

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Supporting Information Available

Details about how prior nonmarket valuation studies, U.S. EPA Regulatory Impact Assessments, and abatement costs (updated); details about how SRCs were used with airshed emissions data to estimate changes in the ambient concentrations of O_3 and $PM_{2.5}$; details of how BenMAP software was used to estimate health outcomes and the economic benefits from a reduction in NO_x emissions; details on the sources and calculation of estimates for Figures 1 and 2. This material is available free of charge via the Internet at http://pubs.acs.org.

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