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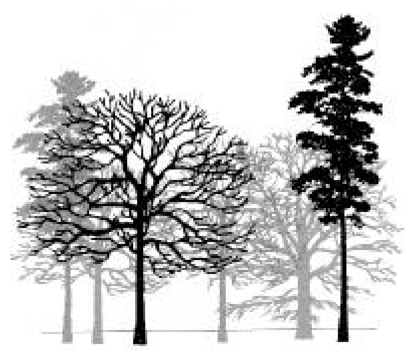
Chesapeake Bay Program

Nitrogen Dynamics in Forested Watersheds of the Chesapeake Bay



17 – 19 June, 1997
Frostburg, MD

M.S. Castro, K.N. Eshleman, R.P. Morgan II,
S.W. Seagle, R.H. Gardner, and L.F. Pitelka

STAC Publication 97-3

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STAC members come primarily from universities, research institutions, and federal agencies. Members are selected on the basis of their disciplines, perspectives, and information resources needed by the Program.

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Acknowledgements

Workshop Steering Committee:

Mark Castro (Chair)	University of Maryland – AL, UMCES
Usha Govindarajulu (Coordinator)	Chesapeake Research Consortium
David DeWalle	Pennsylvania State University
Keith Eshleman	University of Maryland – AL, UMCES
Bob Goldstain	Electric Power Research Institute
Rick Herd	Allegheny Power System
Paul Miller	MD Department of Natural Resources
Kent Mountford	US EPA Chesapeake Bay Program
William Peterjohn	West Virginia University
Steve Seagle	University of Maryland – AL, UMCES
John Sherwell	MD Department of Natural Resources
Al Todd	US EPA Chesapeake Bay Program

Recorders:

Usha Govindarajulu, Amy Kover, Mary Conley

Layout and Editing

Katrin O’Connell

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Chesapeake Research Consortium, Inc.
645 Contees Wharf Road
Edgewater, Maryland 21037-0028
Telephone: 301-261-4500; 410-798-1283
Fax: 410-798-0816; e-mail: crc@chesapeake.org

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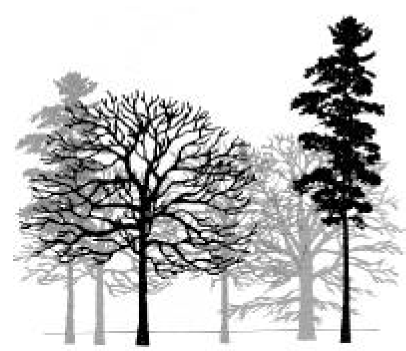

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Workshop Participants:

Mary Beth Adams	USFS	Jeannine Hammer	Allegheny Power
Richard Alexander	USGS - NAWQA	Dan Harmon	U of MD - AL
Larry Band	U of Toronto	Rick Herd	Allegheny Power
Tim Banfield	Allegheny Power	John Horn	USFS
Thomas Birch	USFS	Norb Jaworski	US EPA
Karl Blankenship	Alliance CB	Dale Johnson	DRI
Don Boesch	U of MD	Jeffrey Klopatek	Arizona State U
Daniel Boone	UMS - MEES	Amy Kover	CRC
Stephen Boyce	USFS	Greg Lawrence	USGS
Ishi Buffam	U of VA	Lewis Linker	US EPA
Doug Burns	USGS	Jim Lynch	Penn State
Mark Castro	U of MD - AL	Doug MacCleery	USFS
Craig Caupp	FSU	Paul Miller	MD DNR
Cassie Chimka	U of VA	Ray Morgan, II	U of MD - AL
Mary Conley	CRC/NOAA	Kent Mountford	US EPA
Dave Correll	SERC	Peter Murdoch	USGS
Bill Curry	U of MD - AL	William Peterjohn	West Virginia U
David DeWalle	Penn State	Lou Pitelka	U of MD - AL
Keith Eshleman	U of MD - AL	Steve Seagle	U of MD - AL
Thomas Fisher	U of MD - HPEL	Durland Schumway	FSU
Jim Galloway	U of VA	Gary Shenk	US EPA
Bob Gardner	U of MD - AL	John Sherwell	MD DNR
Frank Gilliam	Marshall U	Brian Sturtevant	UMS – MEES
Bob Goldstein	EPRI	Karen Summers	TetraTech
Usha Govindarajulu	CRC	Al Todd	USFS – CBPO
David Grigal	U of Minnesota	Rich Valigura	NOAA
Grant Gross	CRC	Robert Webster	MD DNR
Morgan Grove	USFS	Don Weller	SERC

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I. Executive Summary

To help increase our understanding of nitrogen (N) dynamics in forested watersheds of the Chesapeake Bay, the Appalachian Laboratory of the University of Maryland Center for Environmental Science organized and hosted a workshop in Frostburg, Maryland on June 17-19, 1997. This workshop was sponsored by the Scientific and Technical Advisory Committee of the Chesapeake Bay Program, the United States Forest Service, Maryland Department of Natural Resources, Allegheny Power Company, Baltimore Gas and Electric Company and the Electric Power Research Institute. There were a total of 56 participants from universities, state and federal agencies, the electric utility industry and included scientists with expertise in many disciplines, such as atmospheric sciences, forest ecology, soil science, entomology, computer modeling, and hydrology. The three main goals of the workshop were to: (1) synthesize and evaluate current understanding of N dynamics in forested watersheds of the Chesapeake Bay, (2) identify the major uncertainties and (3) develop a strategy to reduce these uncertainties.

The information necessary to accomplish these goals was provided by 6 plenary sessions in which speakers discussed current understanding of the physical, chemical and biological factors thought to influence N dynamics in forested watersheds. After considerable discussion, the workshop participants, by consensus, produced the following statements to summarize our current understanding of N dynamics in forested watersheds of the Chesapeake Bay.

- ***Different forested watersheds within the Chesapeake Bay watershed and surrounding regions that have been extensively monitored show dissimilar patterns of N export. Although there are a number of potential explanations, no general consensus has emerged to explain these patterns.***
- ***There is not enough data on long-term trends of N dynamics and losses from forested watersheds in the Chesapeake Bay region.***
- ***In forests where total N inputs and outputs have been measured (approx. 25 sites), stream water N outputs are less than N inputs. Thus, most forests of the Chesapeake Bay watershed are accumulating N.***
- ***Among different forested watersheds, annual N losses are not well correlated with annual rates of atmospheric N deposition, in part because forests can accumulate N.***
- ***Disturbance (e.g., harvesting, insect defoliation, fire) generally increases N export for a short time period (1 to 5 years).***
- ***Past land-use is an important factor affecting rates of N accumulation and total N losses from forests; the role of past land-use in explaining current patterns of N losses from forests has not been adequately evaluated for the Chesapeake Bay region.***
- ***The greatest potential future impacts of forests on N inputs to the Bay will come from losses of forest land to agriculture or urban-surburban growth; such conversion will result in increased export of N from the land to the Chesapeake Bay.***
- ***The roles of nitrogen fixation and denitrification in accounting for observed patterns in N budgets of Chesapeake Bay forests are unknown and difficult to assess.***

These consensus statements indicate that there is considerable uncertainty in our knowledge of the factors controlling N export and retention by forested watersheds of the Chesapeake Bay. The workshop participants agreed that comprehensive regional surveys and manipulation experiments were needed to reduce this uncertainty. Regional surveys would place bounds on the uncertainty of the N export, identify sites that have unusual export rates that require further study and identify watershed characteristics that affect N export. The manipulation experiments are needed to quantify the processes controlling N export, describe how these processes change quantitatively during and after disturbances, and improve our ability to predict future N export from forested watersheds.

II. Introduction

Forests are the dominant land-use in the Chesapeake Bay watershed. They occupy 58% of the total land area and may be the second (cropland is first) most important source of N to the Chesapeake Bay (Linker et al., 1996). Results from recent watershed studies, however, indicate that N export from forested watersheds of the Chesapeake Bay has not been quantified with great accuracy, is subject to significant spatial and temporal variability (Morgan et al., 1994; Eshleman et al., 1995; Dow and DeWalle, 1996; Wigington et al., 1996; Gardner et al., 1996), and may be increasing over the long-term as secondary growth forests reach maturity (Peterjohn et al., 1996). Many factors, such as atmospheric deposition, land-use history, forest type and age, herbivore outbreaks, and random hydrological events, may be in part or entirely responsible for N losses from forested watersheds. Unfortunately, we do not know the role and relative importance of these factors in controlling N export, but this information is critical to accurately predict and manage N losses from forested watersheds.

To help increase our understanding of N dynamics in forested watersheds of the Chesapeake Bay, the Appalachian Laboratory of the University of Maryland Center for Environmental Science organized and hosted a workshop in Frostburg, Maryland on June 17-19, 1997. This workshop was sponsored by the Scientific and Technical Advisory Committee of the Chesapeake Bay Program, the United States Forest Service, Maryland Department of Natural Resources, Allegheny Power Company, Baltimore Gas and Electric Company and the Electric Power Research Institute. There were a total of 56 participants from universities, state and federal agencies, the electric utility industry, and included scientists with expertise in many disciplines, such as atmospheric sciences, forest ecology, soil science, entomology, computer modeling, and hydrology. The three main goals of the workshop were to: (1) synthesize and evaluate current understanding of N dynamics in forested watersheds of the Chesapeake Bay, (2) identify the major uncertainties, and (3) develop a strategy to reduce these uncertainties.

There were 6 plenary sessions in which speakers outlined current understanding of the physical, chemical and biological factors thought to influence N dynamics in forested watersheds within and just outside (Catskills, New York and Fernow Experimental Forest, West Virginia) of the Chesapeake Bay watershed. This report summarizes these presentations and workshop discussions. In the first section (III), we briefly describe current understanding and uncertainties of N dynamics in forested watersheds of the Chesapeake Bay region. In the second section (IV), we describe our understanding of how atmospheric deposition, insect defoliation, harvesting and land-use history affect N export from these watersheds. In the third section (V), we evaluate the Chesapeake Bay watershed model for predicting N export from forested watersheds. In the final section (VI), we describe the research needed to increase understanding of N dynamics in forested watersheds of the Chesapeake Bay.

III. Assessment of Current Understanding: N Export From Forested Watersheds

Several presentations illustrated large temporal and spatial variations in N export, primarily nitrate, (NO_3^-), from entirely forested small watersheds (size= 2 to 120 km^2) in the Chesapeake Bay region.

Dr. David DeWalle, from Pennsylvania State University, presented results from a literature survey of N export from undeveloped and unglaciated forested watersheds in the region. There were large variations in annual rates of NO^-_3 export from both within and between forested watersheds in the Chesapeake Bay region. Some watersheds had relatively high export rates that ranged from 1 to 8.5 kg N ha^{-1} yr^{-1} with interannual variations of 1 to 5 kg N ha^{-1} yr^{-1} . These watersheds were located in southwestern Pennsylvania, northwestern and central Maryland, and northeastern West Virginia. At the other extreme, some watersheds had low export rates, ranging from 0.02 to 0.7 kg N ha^{-1} yr^{-1}, with little or no interannual variations. These watersheds were found throughout Virginia, in coastal and central Maryland and central Pennsylvania.

Potential explanations for this regional pattern include regional variations in atmospheric N inputs, watershed hydrology, forest type and age and insect defoliation. Based on limited data[1], DeWalle suggested that the spatial variations were not due any of these factors, but were related to variations in site fertility. The more fertile sites generally had higher rates of net nitrogen mineralization, net nitrification and NO_3^- export compared to low fertility sites, but the reasons for the differences in site fertility are not known.

Dr. Keith Eshleman, from the Appalachian Laboratory of the University of Maryland Center for Environmental Science, described temporal variations in N export from forested watersheds during both episodic runoff events and insect defoliation outbreaks. Results from his episodic work suggest that major runoff events significantly increase stream water NO_3^- fluxes from forested watersheds. He showed that for the 1992 to 1995 water years, 50% of the NO_3^- export from two forested watersheds in Virginia occurred in 10% of the time. Dr. Eshleman also described the impact of gypsy moth defoliation on NO^-_3 fluxes from the White Oak Run watershed in the Shenandoah National Park, Virginia. For 10 years before the defoliation (1980-1990), annual NO^-_3 fluxes ranged from close to the detection limits up to 0.35 kg N ha^{-1} yr^{-1}. During the first year of the defoliation, stream water NO^-_3 fluxes increased to 1.75 kg N ha^{-1} yr^{-1}. For the next 2 years (1992 and 1993), the annual NO^-_3 flux increased to 4.55 kg N ha^{-1} yr^{-1}. Over the following 2 years, the annual fluxes decreased; in 1995 the annual flux was 1.05 kg N ha^{-1} yr^{-1}. This temporal pattern also appeared in other forest watersheds in Virginia and western Maryland over the 1990 to 1995 time period, coincident with gypsy moth activity. Unfortunately, the historical record of N export from these watersheds started in 1990, so there is little pre-defoliation data.

Dr. David Correll, from the Smithsonian Environmental Research Center (SERC), presented results from a 1992-1993 study that examined dissolved N (ammonium; NH_4^+, NO^-_3, and dissolved organic nitrogen; DON) export from a total of 153 streams located in six large mixed land-use watershed “clusters” (Correll et al., 1994; Correll and Weller, 1997). The major finding of this work was that land-use appears to be a very important controller of N export from these “clusters”. For example, all forms of N export were always highest for streams draining watersheds dominated by agriculture and lowest from watersheds dominated by forests. For the primarily forested watersheds (80 to 100% forested), NO_3^- concentrations were highly variable, ranging from 2.4 to 114 µmoles $liter^{-1}$, and there were no consistent seasonal patterns. Ammonium and DON concentrations ranged from 0.5 to 5.9 µmoles $liter^{-1}$ and 8.4 to 20.1 µmoles $liter^{-1}$,

[1] Only 12 data sources including 25 watersheds were found in the region; 8 data sources and 20 watersheds were in the Chesapeake Bay watershed. The total area associated with these 20 watersheds covered only 0.3 % of the total forested area in the Chesapeake Bay watershed. Most of these watershed studies had a duration of 1 to 5 years. Three watersheds have been studied for 17-20+ years.

respectively. Dissolved organic nitrogen accounted for 11 to 53% of the total dissolved N export, suggesting that DON can make a significant contribution to the total N export.

Collectively, these presentations and others at the workshop (e.g. Beth Adams (USFS), Pete Murdoch (USGS), Doug Burns (USGS), Dale Johnson(DRI)) highlighted some important areas of uncertainty associated with our understanding of (1) the processes controlling N export from forested watersheds and (2) quantification of the rates of N export from forested watersheds. Since N processes include the effects of both *transport* and *transformation* of N species in the watershed, the lack of understanding of physical (primarily hydrological) and biogeochemical processes in forested watersheds must be taken into account. The relative importance of transport and transformation processes in regulating N losses is often difficult to resolve, since these processes are usually highly interactive. In very few cases are these processes understood in sufficient detail to determine which process is limiting. Uncertainties in quantifying the temporal and spatial variations in rates of N export from forested watersheds to surface waters limits the ability of investigators to verify proposed mechanisms of N leakage (N saturation, forest disturbance, climatic anomalies and forest succession).

Uncertainties associated with hydrological transport mechanisms are considerable, as highlighted in presentations by Doug Burns (USGS), Pete Murdoch (USGS), and Larry Band (University of Toronto). All three presentations noted the potential significance of generation of runoff (and N) from transiently-saturated “source areas”, despite the difficulties associated with experimentally quantifying physical runoff mechanisms at the watershed-scale. Field studies of forested watersheds in the Catskills illustrate the fact that many watershed measurements integrate processes and rates over relatively large spatial areas, making it very difficult to “deconvolve” the contributions to runoff from smaller portions of the landscape (e.g., riparian areas). In some cases, experimental studies of runoff generation—such as those making use of natural tracers (i.e., oxygen-18, chloride, etc.) tend to support the hypothesis that runoff generation in the region occurs by such a “saturation overland flow” mechanism, but the ability to identify, locate and quantify these runoff-producing zones remains elusive. In particular, Band’s theoretical study of data from the Turkey Lakes watersheds in Ontario appeared to support the use of a “catenary index” approach in which export of N is highest in areas where N is most easily flushed from (and readily produced by) watershed soils.

According to Dale Johnson, who led the Integrated Forest Study (IFS) and has written a review paper on the factors controlling N losses from forests, the transformation processes involving inorganic N are fairly well-established in intact forest ecosystems, although rates of two processes that affect N gas exchange with the atmosphere are highly uncertain. Denitrification, the conversion of NO_3^- to N_2, has not been quantified in most forested watersheds, although rates have often been found to be quite low, presumably due to the high redox potential of most forest soils. Nitrogen fixation, the conversion of N_2 to NH_4^+, has rarely been measured in forests, although N fixation rates are known to be relatively high in systems dominated by symbiotic N fixers (e.g., red alder, black locust, etc.). Shifts in N transformation processes in forest ecosystems caused by deforestation (logging), herbivorous insect defoliation, hurricanes, or fire are only qualitatively known, but are believed to be very significant. Shifts in N processing due to disturbance and forest succession have been established for some well-known watersheds in other regions (e.g., Hubbard Brook), but comparable field studies within forests of the Chesapeake Bay watershed have not been undertaken.

There is still considerable uncertainty in quantifying N export rates from Chesapeake Bay forested watersheds. First of all, few controlled, long-term (10 years) experimental studies that quantify N export from forested watersheds have been conducted in the Chesapeake Bay watershed, so estimates of among-watershed variability (such as presented by Dave DeWalle) are by necessity based on little data that was collected using different methods and during different time periods. Second, most watershed studies have not measured streamwater export of all forms of N including dissolved inorganic N (DIN = NO_3^- + NH_4^+), DON, and particulate organic N (PON). In some Chesapeake forests, export of DON and PON is quite large, suggesting that N export rates based only on DIN measurements may considerably underestimate total N flux to surface waters. Third, quantification of annual N export rates is highly dependent on measurements during stormflow periods, which can dominate the total annual flux of both water and N. Finally, even fewer watershed studies have examined long-term changes in N export as a function of changing atmospheric N inputs, disturbance, forest succession, insect defoliation, and harvesting. Three exceptions are the studies by (1) Mary Beth Adams at the Fernow Experimental Forest (West Virginia) where 20+ years of data seem to support the N saturation hypothesis, (2) Dave Correll's work in an old-growth forest at SERC over the past 20+ years does not support the N saturation hypothesis and (3) Keith Eshleman and his co-workers have analyzed long-term (17-years) data for White Oak Run in Shenandoah National Park that support a disturbance (gypsy moth defoliation) hypothesis for N leakage.

IV. Effects of Disturbances on Forest N Dynamics

Undisturbed and aggrading temperate forests have been shown to store large amounts of N, 2 to 8 ton ha^{-1}, mainly as organic N in soils, and tightly cycle the available inorganic N (Vitousek et al.,1979; Johnson, 1992). Streamwater outputs of inorganic N are usually small (<1kg N ha^{-1} yr^{-1}) and confined to periods of dormancy and high water flux, such as snowmelt. Significant N export is expected to occur only after these forests reach maturity (Vitousek and Reiners, 1975).

Many temperate forests, however, are influenced in a variety of ways by both human activities and natural disturbances. Some of these disturbances are obvious, such as forest harvesting and insect defoliation that alter both physical and chemical characteristics. Other disturbances are more subtle, such as elevated inputs of N from atmospheric deposition and climatic variations. All of these disturbances, however, have the potential to increase N export from forested watersheds. Not unlike many forests in the Mid-Atlantic Region, forests in the Chesapeake Bay watershed are subjected to substantial harvesting (Cooksey and Todd, 1996), have some of the highest atmospheric N deposition rates in the United States (Peterjohn et al., 1996), and experience periodic insect defoliation (Webb et al., 1995) and random hydrological events (Hyer et al., 1995). However, our understanding of the impacts of these disturbances on N export from forested watersheds of the Chesapeake Bay is not well-known.

IV-A. Atmospheric Deposition (N-Saturation)

Past research investigating the effects of atmospheric N deposition on forested watersheds has led to the concept of N saturation. Nitrogen saturation occurs when the availability of NH_4^+ and NO_3^- in forest soils exceeds the biological demand of the ecosystem for N. Once the N retention capacity is exceeded, the excess N may leach out of forests into streams and groundwater, degrading water quality, increasing cation export, and creating nutrient imbalances in forest vegetation. Symptoms of N saturation include nitrification rates that approach mineralization rates, elevated concentration of NO_3^- in soil solution or stream water, a close balance between atmospheric inputs of inorganic N and stream or groundwater outputs of inorganic N, and high rates of nitrous oxide emission from forest soils. Several of these symptoms have been documented in forested watersheds in Europe (e.g. Emmett et al., 1993).

Although forested watersheds in the Chesapeake Bay region have some of the highest atmospheric N deposition rates in the United States, particularly those in the Appalachian Plateau physiographic province, only one of these watersheds shows any symptoms of N saturation. Forests at the Fernow Experimental Forests (Parsons, West Virginia) exhibit all of the symptoms listed above. For example, atmospheric inputs of inorganic N are similar to the output rates. Although other forested watersheds in the Chesapeake Bay region have comparable rates of atmospheric N deposition, they have relatively low rates of stream water N export, suggesting that they are not N saturated, but are accumulating N. Additional evidence that does not support the N saturation concept comes from the work by Dr. Correll in an old-growth forest at SERC. This mature forested watershed has not been disturbed, except by atmospheric deposition, over the past 300-years. This watershed has relatively high atmospheric N deposition rates of 8 to 11 kg N ha^{-1} yr^{-1}, but exports little inorganic N (0.1 kg N ha^{-1} yr^{-1}). Most of the N export is in the form of DON. Collectively, these results suggest that forested watersheds in the Chesapeake Bay region that have been studied to date (approx. 25 sites), are still accumulating N and are not N saturated.

Atmospheric deposition may be an important source of N for the Chesapeake Bay. Past studies suggest that the atmosphere accounts for 22 to 44% of the total N loadings to the Bay (Tyler, 1988; Fisher and Oppenheimer, 1991; Hinga et al., 1991; Boynton et al., 1995). A more recent assessment suggests that atmospheric N deposition accounts for 50 to 80 % of the total N loadings from the major tributaries to the Chesapeake Bay over the 1990-1993 period (Jaworski, 1997). All of these estimates, however, are uncertain because of gaps in our knowledge of atmospheric inputs, particularly dry deposition, wet deposition of DON, and N fixation and the retention and export of N by the watershed (Valigura et al., 1994; Gardner et al., 1996).

Presentations by Drs. Galloway (University of Virginia) and Lynch (Penn State) highlighted major uncertainties in understanding of atmospheric deposition to the Chesapeake Bay and its watershed. Dr Galloway discussed the emissions and deposition of NH_x and wet deposition of DON. Dr. Lynch's presentation focused on spatial and temporal variations of wet deposition of inorganic N to the Chesapeake Bay watershed. Dr. Jaworski (retired-USEPA) described the results from a recent analysis designed to assess the contribution that atmospheric deposition makes to N loadings to the Chesapeake Bay.

There appear to be two important gaps in knowledge of NH_x emissions. First, we do not know the size or shape of the NH_x airshed for the Chesapeake Bay. As a result, we currently can not make accurate predictions about how changes in NH_x emissions affect the Chesapeake Bay. Prior to using the Regional Atmospheric Deposition Model (RADM) to estimate the NH_x airshed, RADM should be thoroughly assessed to determine if it can accurately predict NH_x deposition. Second, county level NH_x emission inventory data are based on few field measurements and may therefore be inaccurate. At the very least, more *in situ* field measurements of NH_x emissions from agricultural sources are needed for comparison with modeled results and to strengthen NH_x emission inventories for the Chesapeake Bay region.

The greatest gap in our knowledge of NH_x deposition is the quantification of dry deposition. Current techniques for the measurement of the atmospheric concentrations and dry deposition of NH_3 gas and NH_4^+ aerosols are highly uncertain and site specific, making extrapolation to other sites problematic without field validation and verification. Studies of dry deposition rates of many N species, particularly NH_4^+ and NH_3, should be conducted within the Chesapeake Bay region and over the waters of the Chesapeake Bay. Integrated monitoring sites of emissions and deposition should be established within the airshed.

Dr. Galloway reported that wet deposition in coastal Delaware contains a highly labile and reactive fraction of DON that disappears within hours of collection and is not converted to inorganic N. This rate of disappearance is reduced by decreasing the temperature of the collection bucket. These results suggest that previous estimates may have underestimated the importance of wet deposition inputs of DON to the Chesapeake Bay region.

Dr. Lynch’s presentation highlighted the large temporal and spatial variations in wet deposition rates of inorganic N to the Chesapeake Bay region. He described his wet deposition model that operates at a very fine spatial scale (30 x 30 m) which can be used to estimate the wet deposition patterns over complex landscapes typical of the upland portion of the Chesapeake Bay watershed (about 2/3 of the entire watershed). This model has much better spatial resolution than previous predictions of wet deposition to the Chesapeake Bay watershed (Valigura et al., 1996). This model, however, needs to be thoroughly tested at independent sites in the Chesapeake Bay region that were not used in model development.

Norb Jaworski used a linear regression model to predict the contribution that atmospheric N deposition made to the inorganic and total N loads of the major rivers of the Chesapeake Bay watershed (Susquehanna, Rappahonnock, James, Potomac and York) from 1990 to 1993. Results from this model suggest that atmospheric N deposition contributed between 50 and 80% of the total N transport by these rivers to the Chesapeake Bay. Jaworski’s estimates are substantially higher than previous estimates that ranged from 22 to 44 % (Tyler, 1988; Fisher and Oppenheimer, 1991; Hinga et al., 1991; Boynton et al., 1995).

IV-B. Gypsy Moth, Harvesting and Land-use Change

Unlike the subtle chemical disturbance of atmospheric N deposition, forested watersheds in the Chesapeake Bay region have also experienced many obvious physical disturbances, such as insect defoliation, harvesting and land-use changes throughout recent history (last 300 years). The workshop participants agreed that insect defoliation and forest harvesting generally increase N export for short time periods (1 to 5 years). For example, Eshleman described the short-term (up to 5 years) impact of gypsy moth defoliation on NO_3^- fluxes from the White Oak Run watershed in the Shenandoah National Park, Virginia, and possibly other watersheds in the Chesapeake Bay region. Lynch reported that a commercial clear-cut with best management practices applied to a watershed in PA significantly increased N export above the control watershed for 3 years after the harvest.

Superimposed on these short-term disturbances, are the disturbances caused by human and natural processes that have occurred over the past last 300 years or more. Although the land-use history of the Chesapeake Bay watershed, starting with the Native Americans in the early 1600's, is generally known at the broad scale (McCleary, 1992), we know very little about the long-term (past 300 years) history of many of the small-scale forested watersheds that have been used in many of the past and ongoing N export studies. This is a major gap in our ability to explain N export patterns because past land-use activities may significantly alter current soil N dynamics. For example, a regional survey of 159 small watersheds in central New England indicated that there were only 3 watersheds that had no detectable NO_3^- export (Hornbeck et al., 1996). Upon close examination of 1 of these 3 watersheds, the Cone Pond watershed, it was learned that 85 % of this watershed was severely burned in 1820. This fire apparently disturbed the soil N cycle such that the present conditions still do not favor the production of NO_3^- beyond that immobilized by the microbial and plant communities and therefore there is no NO_3^- available to be exported out of the watershed by stream and ground waters . Better historical data about past land use history is needed.

Additionally, future land-use change is also likely to affect N loadings to the Chesapeake Bay. Future land-use changes, driven by population growth, are projected to reduce the amount of forested land in the Chesapeake Bay watershed. In 1970, forests occupied 62% of the watershed. However, since that time, urban expansion and suburbanization has consumed forested land at a rate of 100 acres a day. The human population in the Chesapeake Bay watershed is projected to increase from 14.7 million in 1990 to 17.4 million by the year 2020. It is projected this population increase will consume 636,000 acres of forest and farmland for new housing developments (Cooksey and Todd, 1996). The conversion of forest lands to other land use will increase N export to the Chesapeake Bay. In fact, the workshop participants agreed that the greatest potential future impact of forests on N inputs to the Bay would come for the loss of forests to other land uses.

V. Using HSPF to Model N Export From the Chesapeake Bay Watershed

The primary model that is used to simulate N transport within the Chesapeake Bay watershed is the Hydrological Simulation Program - FORTRAN (HSPF). HSPF receives atmospheric N deposition data from NOAA's regression model (Valigura et al., 1996) and interfaces N input to terrestrial systems with hydrodynamic processes to (1) calculate N (and phosphorus and sediment) runoff within hydrological "segments" of the Bay watershed, (2) merge water and N fluxes from watershed segments into river segments subjected to various in-stream transformations, and (3) summarize delivered N loads to the Chesapeake Bay from each of the major tributaries (Donigian et al., 1995; Linker et al., 1996).

The current watershed model can be characterized as a top-down system that seeks general magnitudes and temporal patterns of N loading to the Chesapeake Bay, while sacrificing spatial and, depending on land use, process-level resolution. For its intended purposes, refining public policy and more clearly defining non-point N pollution problems, HSPF and associated models have been successful. However, one hallmark of that success is the necessity to refine the models to provide specific aid in solving smaller-scale questions related to spatial patterns of N dynamics within different land uses.

Some areas of primary concern for HSPF application is the loading of N to forests, forest processing of N, and N export from forests. Estimates of regional and sub-regional atmospheric N loading to forests of the Chesapeake Bay watershed need greater resolution than currently provided by the regression model (Valigura et al., 1996). In particular, topographic effects and forest canopy "roughness" need greater consideration to provide truly representative loadings at finer resolution. Phases I and II of HSPF development did not include detailed N processing within forests, but relied on generalized loading functions. For example, forests were assumed to have the lowest unit area N input to surface waters of 3.4 kg N ha^{-1}, compared to 7.9 kg N ha^{-1} for pastures, 11 kg N ha^{-1} for hay and urban, and 25.5 kg N ha^{-1} for conventional tillage agriculture (Linker et al., 1996). Despite having the lowest unit area input, the watershed model predicts that forests contribute 27 % of the total N to the Chesapeake Bay, second only to cropland at 42% (Linker et al., 1996). These model predictions, however, are highly uncertain because the loading factor (3.4 kg N ha^{-1}) assigned to forests may not be representative of the actual N export.

Enhancements for phases III and IV of HSPF include: expansion of the forest organic compartments in the model from one to four compartments. These new compartments produce: (1) finer resolution of the labile and recalcitrant carbon and N pools, (2) add above and below ground soil and litter components, (3) compute gaseous N losses from forest soils and (4) account for the conversion kinetics of atmospheric N to soil N. This additional detail of N processing in forests is aimed at more accurately predicting forest N losses by increasing greater understanding of N processing in forest ecosystems. Replacement of forest N loading functions with forest N processing will also bring increased realism to the relationship between N inputs and outputs. In particular, stream water N outputs will no longer be considered to be a linear function of atmospheric N inputs.

Spatial problems of nutrient fluxes must eventually be addressed within HSPF. It is unclear the degree to which spatial variation in forest composition and soil types will be incorporated into model improvements. However, particular attention should be paid to decomposition and N processing differences between radically different forest types that occur across the watershed. In a landscape context, HSPF does not currently consider forest position relative to topography and other land uses. For example, forests downslope from other land uses, such as cropland, are subject to both atmospheric and hydrological N input, which collectively influence forest N processes and N retention/export properties of the forest. These collective influences can be most influential for water quality in forests that serve as riparian buffers.

Addressing details of spatial applications and N processing further complicates the calibration and testing of HSPF by increasing the number of parameters to be estimated, the time required to examine parameter sensitivity, and the number of independent, different scale, data sets needed to compare with model results. At the heart of this model testing is the difficult question of whether small scale N process modeling can cumulatively represent landscape and regional N flows. Nonetheless, confident application of the model can only be based in thorough model verification.

Another fundamental problem with application of HSPF to the problem of modeling N dynamics of the Chesapeake Bay watershed is that the model was not developed to provide *dynamic* forecasts of water quality given various land use/land cover change scenarios (e.g., forest cutting, forest defoliation, forest succession, increased atmospheric N loading, etc.). These change scenarios are all known to affect N cycling and rates of N leakage to surface waters. Rather, the primary use of HSPF in modeling the Chesapeake Bay watershed is more suitably characterized as a "bookkeeping" exercise. Each of these scenarios would expectedly cause a different N leakage response, yet there is no way to use any HSPF version to implement such a scenario in a dynamic mode. For example, forest clearing can be implemented, but only by converting some amount of forested acreage to an alternate land use (e.g., pasture land)—in which case that acreage is assumed to instantaneously behave as all other pasture land in the particular land segment behaves. Transient, distributed processes such as succession and disturbance have been shown to have a dramatic effect on forest N cycling and leakage—yet these processes are too complex to model using a lumped parameter, bookkeeping model like HSPF. To consider such scenarios and their effects on N leakage, other models are needed which are more structurally compatible with the goal of simulating transient N leakage from forested watersheds or from other land use types.

VI. Recommendations

The greatest uncertainty in our understanding of N export from forests in the Chesapeake Bay watershed can be divided into two areas: (1) the uncertainty associated with current estimates of N export from forests and (2) the prediction of future N export from forests. To date, there is considerable variation (0.01 to 8.5 kg N ha^{-1} yr^{-1}) in annual rates of N export from forested watersheds. These data were derived from very few studies, most of which were of short duration and the reasons for this variation have not been identified with a high degree of confidence. To improve current estimates of N export from forested watersheds, comprehensive regional surveys must be conducted. We must establish a regional network of nested, gaged forested watersheds for which N export (total N, organic N and inorganic N) would be quantified over a 5 - 10 year period. This network should consist of approximately 3-5 nested watersheds in each of the physiographic provinces in the Chesapeake Bay watershed. The selected watersheds should represent the major forest types, geology, soils, and climate observed in the Chesapeake Bay region. Stream water samples should be collected using the same sampling methods under both base and storm flow conditions. Samples should be analyzed using the same methods and possibly by the same laboratory. Data would be used to estimate the average annual N export and place bounds on the uncertainty of the export, identify sites that have unusual export rates for further study and help identify watershed characteristics that affect N export.

Unfortunately, regional surveys are not likely to improve our ability to predict future changes in N export due to human and natural disturbances. To improve our predictive ability we need to conduct a series of experimental manipulations made in conjunction with process-level measurements. First, we need a better understanding of the complete N cycle in forested watersheds. To do this we must incorporate into both existing and future field studies comparable measurements of N cycling in forests. We need to measure atmospheric inputs (deposition and fixation), soil and detrital N dynamics (mineralization, nitrification, and denitrification), soil water solutions, litterfall, biomass accumulation, and stream and ground water N export. These measurements should be made in a variety of watersheds with different export rates in many different regions. Next, we need to establish a series of experimental manipulations, such as N additions, tree defoliation, selective harvesting, soil warming and simulated hurricane blowdowns, and compare the changes in the N cycling response variables to those in adjacent control watersheds. These manipulation experiments could be coordinated with planned and future timber management operations. Data from this work would improve our understanding of N dynamics in forested watersheds of the Chesapeake Bay region, enable us to better predict the consequences of future disturbances, and improve our ability to model N dynamics in forested watersheds.

VII. References

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VIII. Workshop Agenda

Tuesday, June 17

A. Background Information

8:00 am Registration (Guild Center, Room 104)

9:00 am Welcome and Introductions (Guild Center, Room 104), Lou Pitelka, Director of AL

9:15 am Overview: logistics, purpose and objectives, Mark S. Castro (AL)

9:30 am Plenary Discussion: **Forests in the Chesapeake Bay Watershed: Important Characteristics, Status, and Projected Trends**, Moderator, Al Todd (USFS); Panel: Steven Boyce (USFS), Douglas MacCleery (USFS) and Thomas Birch (USFS)

11:00 am Plenary Discussion: **Nitrogen Outputs From Forests in the Chesapeake Bay Watershed**, Moderator, Ray Morgan II (AL); Panel: Dave DeWalle (Penn State), Dave Correll (Smithsonian) and Keith Eshleman (AL)

- Are forests important sources of nitrogen to the Bay?
- Are there important spatial and temporal variations?
- Are there important regional gradients?
- Can we explain these patterns?

12:30 pm Lunch (Leake Hospitality Room in the Physical Education Center)

B. Scientific Assessment

1:30 pm Plenary Discussion: **Atmospheric Nitrogen Deposition: Uncertainties, Role in Nitrogen Outputs from Forests**, Moderator, Paul Miller (MDNR); Panel: Jim Galloway (UVa), Jim Lynch (Penn State) and Norb Jaworksi (EPA)

- How well do we know the atmospheric inputs?
- Are atmospheric inputs important drivers of nitrogen losses from forests in the Chesapeake Bay watershed?
- What do we need to know or do to better understand the link between atmospheric deposition and nitrogen losses from forests in the Chesapeake Bay watershed?

3:00 pm Coffee Break (Guild Center, Room 104)

3:30 pm Plenary Discussion: **Physical Factors Controlling Nitrogen Outputs From Forests**, Moderator, Keith Eshleman (AL); Panel: Richard Alexander (USGS), Doug Burns (USGS) and Greg Lawrence (USGS)

- Can nitrogen losses be explained by hydrological events, flushing and retention times, topography and/or other physical factors?
- Do we have the data necessary to evaluate the importance of the physical controls?

- What experiments or monitoring programs need to be implemented or modified to acquire these data?

5:00 pm Discussion of All Presentations, Keith Eshleman (AL)

5:30 pm Adjourn

6:00 pm Dinner (Outside:1st floor balcony behind the Lewis J. Ort Library)

Wednesday, June 18

8:30 am Plenary Discussion: **Biological Factors Controlling Nitrogen Outputs From Forests**, Moderator, Steve Seagle (AL); Panel: Pete Murdoch (USGS), Mary Beth Adams (USFS) and Dale Johnson (DRI)

- Can the patterns of watershed nitrogen losses be explained by variations in vegetation uptake, species composition, forest age, land cover, soil microbial processes, insect defoliation or forest management practices?

10:00 am Coffee Break (Guild Center, Room 104)

10:30 am Discussion Addressing Objectives 1 and 2, Steve Seagle (AEL)

Objective 1. To synthesize and evaluate current understanding of nitrogen dynamics in forests of the Chesapeake Bay watershed.

Objective 2. To identify, rank and quantify (if possible) the factors controlling nitrogen retention and export from forests.

- What evidence is there to elucidate the relative importance of different processes in controlling nitrogen losses?
- Can we rank and quantify the relative importance of the factors controlling nitrogen retention and export?
- What are the uncertainties?

11:30 am Modelling Session I: **Modelling Nitrogen Dynamics in Forests**,Moderator, Bob Goldstein (EPRI); Panel: Morgan Grove (USFS) and Larry Band (University of Toronto)

12:30 pm Lunch (Leake Hospitality Room)

1:30 pm Modelling Session II: **Modelling Nitrogen Dynamics in Forested Landscapes within Larger Watershed and Assessment Models**, Moderator, Bob Goldstein (EPRI), Panel: Gary Shenk (EPA) and Karen Summers (Tetra Tech)

2:30 pm Plenary Discussion of Objective 3 and Modelling, Moderator, Bob Goldstein (EPRI)

Objective 3. Identify the best approaches to accurately extrapolate from small catchment studies to the entire forested portion of the Chesapeake Bay watershed.

- How do we extrapolate from catchment studies to landscape and regional scales?
- What are the best models/approaches to predict future nitrogen loses from forested landscapes?

- How do they differ?
- What processes do they incorporate?
- What assumptions and unknowns need to be quantified?
- What do we need to know?
- How do we acquire the necessary information?
- How effective is the Chesapeake Bay watershed model at predicting nitrogen export from forests?
- Are there more effective approaches?

3:30 pm Coffee Break (Guild Center, Room 104)

4:00 pm Discussion: Development of a Research Agenda, Lou Pitelka (AL) and Robert Gardner (AL)

Objective 4. To develop a prioritized list of research studies and a strategy for addressing these research needs.

5:00 pm Adjourn

6:00 pm Dinner at Giuseppe's Italian Restaurant (11 Bowery Street, Frostburg)

Thursday, June 19

8:30 am Discussion: Development of a Research Agenda, Lou Pitelka (AL) and Robert Gardner (AL)

- Where are the gaps in our knowledge in nitrogen dynamics in forest ecosystems?
- Which gaps are in greatest need of resolution?
- What is the prognosis for addressing these gaps within a reasonable period of time and with a reasonable budget?
- Where will the funds to support these projects come from?

10:30 am Coffee Break (Guild Center, Room 104)

11:00 am Final Discussion: Research Agenda & Other Issues, Lou Pitelka (AL)

- Did we satisfy the objectives of the workshop?
- Where do we go from here?

12:30 pm Adjourn and Lunch