Environ. Sci. Technol. **2004**, *38,* 3068−3073

Solving Problems Resulting from Solutions: Evolution of a Dual Nutrient Management Strategy for the Eutrophying Neuse River Estuary, North Carolina

HANS W. PAERL,* LEXIA M. VALDES, ALAN R. JOYNER, AND MICHAEL F. PIEHLER

University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, North Carolina 28557

MARTIN E. LEBO

Weyerhaeuser Corporation, Environmental Health and Safety, New Bern, North Carolina 28563

In estuaries, phosphorus (P) and nitrogen (N) inputs generally control freshwater and saltwater primary production, respectively. Improved wastewater P removal and a P-detergent ban in the late 1980s decreased P loading to the nutrient over-enriched Neuse River Estuary, NC, without a contemporaneous reduction in N loading. This led to a decrease in upstream freshwater phytoplankton production and a reduction in nuisance algal blooms. While this nutrient management approach appeared to be effective in reducing the symptoms of freshwater eutrophication, it may have also diminished the upstream algal N filter, promoting N enrichment, relative to P enrichment, and eutrophication of the more saline downstream N-limited waters. Recent N controls implemented by the State of North Carolina should help address the problem. These findings underscore the need for watershed- and basin-scale, dual nutrient (N and P) reduction strategies that consider the entire freshwater−marine continuum as well as hydrologic variability (e.g., hurricanes, floods, droughts) when formulating long-term controls of estuarine eutrophication.

Introduction

Phosphorus (P) is the nutrient most often controlling or limiting freshwater primary production (*1*, *2*). Accordingly, freshwater nutrient management strategies have largely focused on P-input reductions to control nutrient-enhanced primary production or eutrophication (*3*, *4*). Indeed, such reductions have been highly successful at stemming and reversing freshwater eutrophication (*5*). However, as freshwater systems drain into estuarine and coastal ecosystems, nitrogen (N) is most often the dominant limiting nutrient (*6*−*8*). Nitrogen overenrichment has been considered a prime threat to the biological integrity, natural resource value, and ecological condition of estuarine and coastal waters worldwide (*9*, *10*).

While anthropogenic P inputs have been reduced in freshwater segments of many coastal watersheds, N inputs have largely remained unchanged and in some cases have increased (*7*−*11*). As a result, coastal waters are becoming more N enriched relative to P (*10*−*13*). One potential consequence of this inequity in nutrient loading is that P-controlled primary production at the freshwater head of the estuaries may be reducing the capacity of this region to assimilate or filter other limiting nutrients, most notably N. This would potentially allow more efficient N transport downstream to N-sensitive coastal waters, adding to the local anthropogenic N loads already impacting these ecosystems (*14*). Such displacement of the eutrophication gradient could help explain the reported increases in estuarine harmful algal bloom activity (*9*, *15*), hypoxia (*16*, *17*), and declines in fisheries habitats (*12*).

We examined the potential for this scenario in the Neuse River Estuary (NRE), NC (Figure 1), which over the past 40 years has experienced large increases in N and P input associated with urban, industrial, and agricultural development in its watershed (*18*). Excessive nutrient loading was implicated as an cause for the increase in nuisance blue−green algal (cyanobacterial) blooms, which plagued water quality in the upstream freshwater segment of the NRE throughout the late 1970s and 1980s (*18*, *19*). Because the riverine freshwater portion of this system was largely P-limited, emphasis was placed on targeting this nutrient for reduction, which was initiated in the mid- to late 1980s The state of North Carolina has recently begun to address N enrichment of the estuarine portion of the system (TMDL Phase 1, 1999).

Owing to long-term water quality monitoring activities by the State of North Carolina and University research groups, as well as parallel experimental determinations of nutrient cycling and limitation dynamics (*18*, *19*), we were able to construct the nutrient loading record and examine nutrient−production interactions leading up to and following these bloom events. Here, we present a historical analysis and interpretation of the impacts of selective P reductions on nutrient (N and P) loading and phytoplankton production dynamics along the freshwater−marine continuum representing the NRE.

The approximately 30 year period (1970−2003) included in this analysis was also witness to considerable climatic and hydrologic variability, including multi-year periods of drought and elevated rainfall, culminating in a recent (since 1996) increase in Atlantic Basin hurricane activity. This hydrologic variability has affected both nutrient loading and transport and thus was considered in evaluations of long-term, ecosystem-level impacts of nutrient management strategies on eutrophication dynamics in this estuary.

Materials and Methods

Research Site. The NRE is a shallow, coastal plain estuary and a key tributary of the Albemarle−Pamlico Sound system, the United States' second largest estuarine complex and a key fisheries nursery for the mid-Atlantic coastal region (*18*) (Figure 1). This system reflects rapid post-World War II coastal watershed agricultural and urban expansion, accompanied by accelerated N and P production in its basin (*20*). Inputs of N and P to the NRE are dominated by nonpoint sources (>70%). The NRE has experienced a 45% increase in point sources and a 135% increase in nonpoint sources of N and P since the 1960s (*20*). Phytoplankton account for at least 80% of new production of organic matter in the NRE (*19*, *21*); hence, they play a central role in its eutrophication potential. Symptoms of accelerating eutrophication include widespread

* Corresponding author phone: (252) 726-6841; fax: (252) 726-2426; e-mail: hpaerl@email.unc.edu.

10.1021/es0352350 CCC: $27.50
Published on Web 05/01/2004

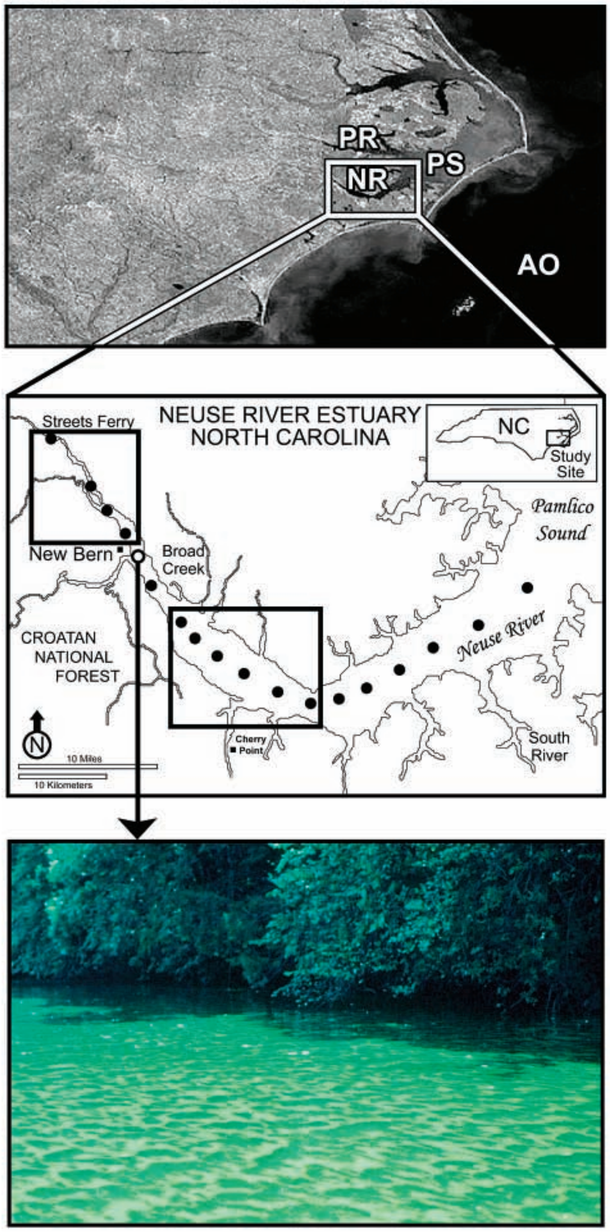

FIGURE 1. Location of the Neuse River Estuary, a subestuary of Pamlico Sound, NC. Shown are the Atlantic Ocean (AO), Pamlico Sound (PS), and the Pamlico and Neuse Rivers (PR and NR). The Neuse River Estuary water quality sites (17 filled circles) monitored by the University of North Carolina's Institute of Marine Sciences are shown in the middle frame. Representative upstream freshwater (Streets Ferry to New Bern) and midestuarine mesohaline (Broad Creek to the bend in the Neuse River) regions, from which the long-term water quality data are shown in detail in Figures 2−4, are delineated as squares. The algal (cyanobacterial) bloom shown in the lower frame occurred at an upstream location (see arrow) in the summer of 1983, prior to the implementation of phosphorus input reductions, which began in the late 1980s (photograph taken by H. Paerl).

phytoplankton blooms, frequent summer and fall hypoxia and anoxia, accompanied by finfish and shellfish kills (*21*−*24*).

Historical Water Quality Monitoring Activities. Since 1970, the NRE has been surveyed for water quality parameters at no less than monthly intervals, increasing to a biweekly frequency in 1994. The data used in this historical analysis were obtained from several State and University water quality monitoring studies and programs, including (1) North Carolina State University (J. E. Hobbie and N. W. Smith, late 1970−1973) (*25*); (2) State of North Carolina (Department of Environment and Natural Resources, Division of Water Quality) Ambient Water Quality Monitoring Program (1971−2002; www.http//h2o.enr.state.nc.us/neuse.htm); (3) East Carolina University (R. Christian and D. Stanley, mid-1980 and 1982 to early 1989); (3) the Weyerhaeuser Co., Water Quality Monitoring Program (1978−1997); and (4) the UNC−CH Institute of Marine Sciences Neuse River Bloom Project and Neuse River Estuary Modeling and Monitoring Study (ModMon, www.marine.unc.edu/neuse/modmon, 1981−1982 and 1985 to present). These programs examined standard indices of nutrient enrichment and water quality status, including dissolved inorganic N (nitrate/nitrite, ammonium), inorganic P (orthophosphate), total P, organic N and P inputs, particulate carbon and N, chlorophyll *a*, and other photopigments diagnostic of major phytoplankton taxonomic groups, dissolved oxygen, turbidity, temperature, salinity, and pH. Collection and analytical protocols and methods used in these programs remained uniform and similar and can be found in Paerl et al. (*21*, *23*), Pinckney et al. (*24*), and the senior author's laboratory website (www-.marine.unc.edu/Paerllab).

Data Compilation. The water quality data that were collected by these programs was merged to produce the most complete historical data set possible for each of the sampling locations shown in Figure 1. The data from stations located between Streets Ferry and New Bern were combined to represent the freshwater upstream region of the estuary, while the data collected from stations located between Broad Creek and the bend in the Neuse River were combined to represent the mesohaline midestuarine region of the estuary. Nutrient and chlorophyll *a* data used in this analysis includes data collected through 2003, with the exception of total P, which was collected through 2002.

Freshwater discharge to the NRE was obtained from the U.S. Geological Survey gauging station (No. 02089500) located at Kinston, NC, approximately 20 km upstream from Streets Ferry, a location downstream of the major nutrient inputs to the NRE, and near the head of the estuary. Nutrient (N and P) loadings to the NRE were calculated by multiplying the average daily freshwater discharge at Kinston by the linearly interpolated surface nutrient concentrations measured at Streets Ferry. In instances when N and P concentration data were scarce at the Streets Ferry sampling station, nutrient data from the other stations in the upstream region were used in the nutrient loading calculations.

Results and Discussion

During the 1980s, efforts to stem eutrophication were focused on the upstream, freshwater segment of the NRE, where nuisance cyanobacterial blooms proliferated and posed serious water quality problems (*18*, *19*) (Figure 1). Because these blooms were shown to be at least partially P-limited, strict P controls were enacted, including a P-detergent ban (January 1988) and wastewater P-discharge limits (*19*, *20*). These steps greatly reduced annual mean total P concentrations, relative to N, at the upstream delivery point to the estuary (Figure 2). The reduction in P loading was also evident at the midestuarine region of the estuary, where mean annual total P concentrations likewise decreased in the late 1980s, following a steady increase earlier in that decade (Figure 2).

As a consequence of the P-reduction strategy and lack of N-load reductions, N concentrations increased relative to P, as illustrated by the increases in both the TN/TP concentration and loading ratios at both the upstream and the midestuarine regions (Figure 3). However, the trend toward increased TN/TP concentration ratios after the P reductions was far more pronounced at the midestuarine region than

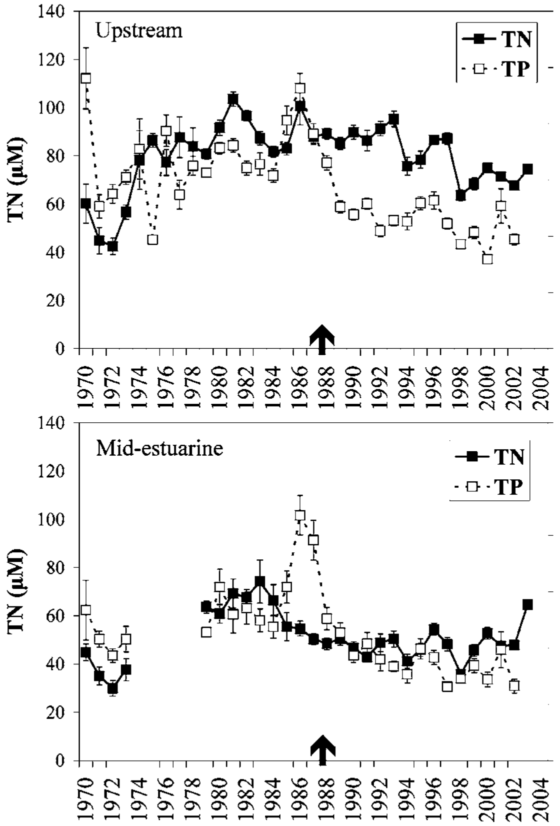

FIGURE 2. Mean annual surface concentrations of total phosphorus (TP) and total nitrogen (TN) at the upstream and midestuarine regions of the Neuse River Estuary. The upstream region represents the main point of freshwater inflow to the estuary. The time of the P detergent ban is indicated with an arrow in each figure. Error bars represent standard error.

at the upstream region, suggesting that downstream N enrichment accompanied the upstream P reductions (Figure 3).

Examinations of chlorophyll *a* (Chl *a*), an indicator of phytoplankton biomass response to nutrient supply, showed relatively high concentrations at the upstream freshwater portion of the estuary during 1978–1987, with the exception of 1982 and 1984, years that coincided with periods of elevated river discharge (Figure 3). Chl *a* concentrations and nuisance cyanobacterial blooms decreased in the late 1980s, shortly after P reductions were initiated, with a very low mean annual Chl *a* level in 1989, the year after the P-detergent ban was in place. Following P reductions and increases in TN/TP, cyanobacterial dominance decreased (chlorophyte and diatom dominance increased), evidence that cyanobacterial dominance tends to decrease in response to increasing N/P ratios in these eutrophic waters (*4*). Chlorophyll *a* concentrations also increased slightly after 1989, however, they never increased to the levels observed in the early to mid-1980s. In contrast, midestuarine, mesohaline Chl *a* concentrations did not show a parallel decrease following the P reductions. Rather, mean annual midestuarine Chl *a* concentrations tended to increase following the P reductions, with 1989–1992, 1994–1996, and 2000–2003 supporting extensive phytoplankton blooms comprised of dinoflagellates, cryptomonads, and to a lesser extent, diatoms (*23*, *24*). The intensity and spatial extent of midestuarine phytoplankton blooms were higher in the 1990s than in the 1980s, when blooms were more prominent in the upper region of the estuary (Figures3 and 4) (*24*). This indicates that the midestuarine blooms increased in magnitude following the P reductions.

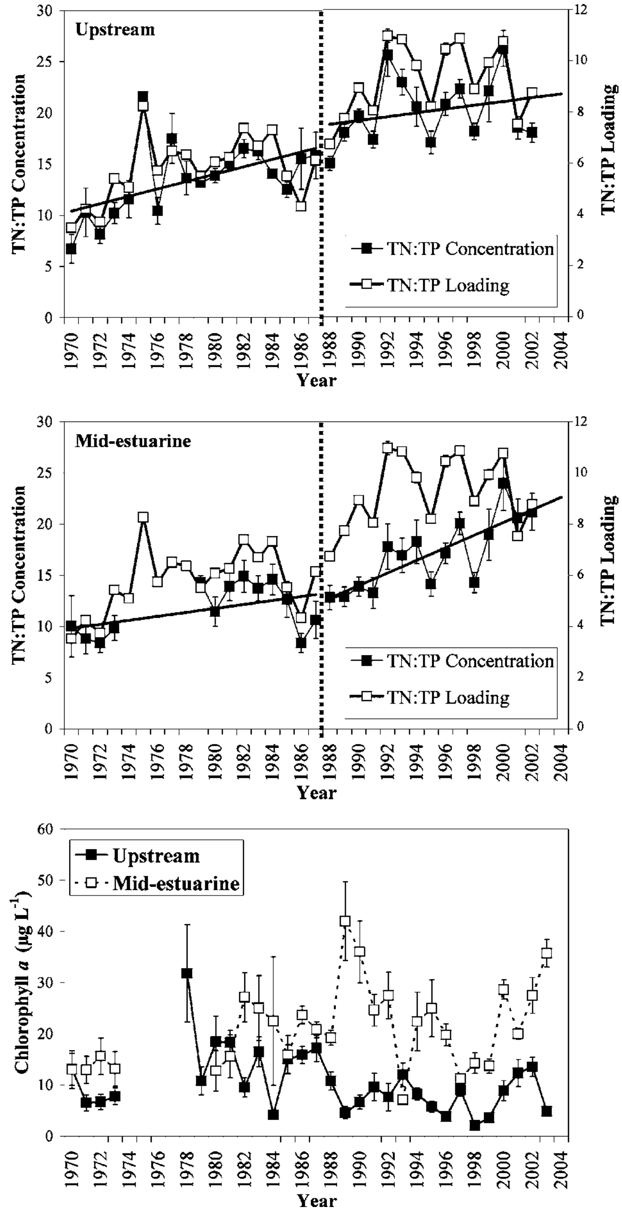

FIGURE 3. Mean annual surface concentration and loading ratios of TN and TP, and mean annual chlorophyll a (Chl a) concentrations at the upstream and mid-estuarine regions of the Neuse River Estuary. Data are plotted from 1970 through 2003. Note that TN:TP loading ratios were calculated for the entire estuary and are therefore equivalent in both the upstream and mid-estuarine panels. The dashed vertical line denotes the time of the P detergent ban. Data were divided into two time periods, before and after the P detergent ban. Linear trend lines are shown for each of the two time periods at both estuarine regions. The missing data points in the historical record of Chla (1974–1977) are due to gaps in the collection of Chl a data. Error bars represent standard error.

During the course of these events, the phytoplankton assemblages showed consistent N limitation throughout the mid- and lower NRE (*23*, *26*), while the upper segment exhibited N and P limitation during spring, with more exclusive N limitation during summer and fall (*23*, *26*). In winter, nutrient and light limitation coexisted (*26*).

Hydrologic variability strongly interacted with nutrient supply to determine when, where, and how phytoplankton blooms responded to nutrient loading scenarios in the NRE (*23*, *24*). The 1970–1995 period proved to be one of fairly normal, seasonal patterns of wet winter–spring months, followed by drier summer–fall periods, with several years

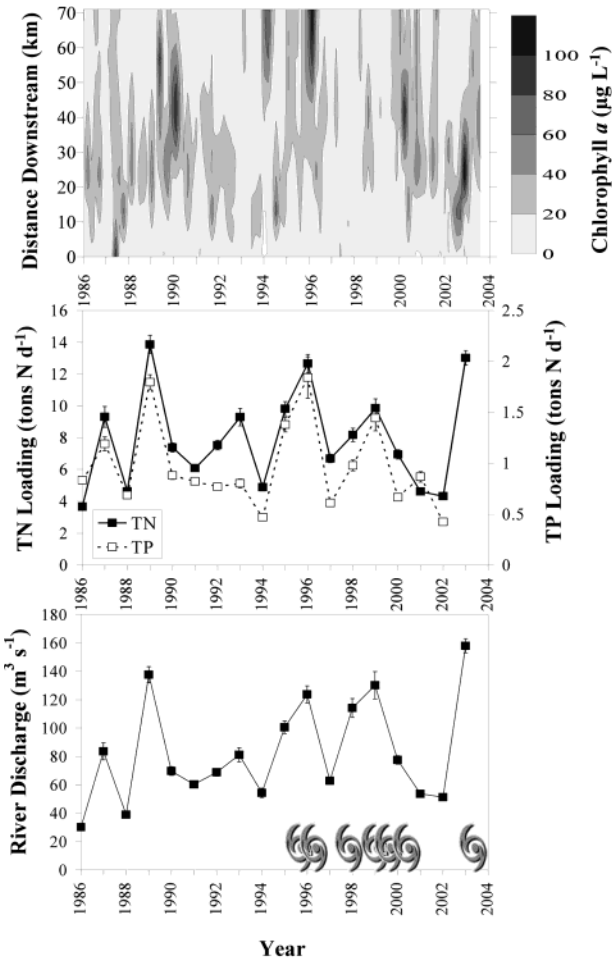

FIGURE 4. Upper frame: distribution and intensity of chlorophyll *a* (Chl *a*) in the Neuse River Estuary between 1986 and 2003. Note the tendency for Chl *a* peaks to be located upstream during the mid 1980s with a migration downstream in the late 1980s and early 1990s. This pattern reversed following the series of hurricanes (indicated in the lower frame) that started to affect the Neuse River Estuary watershed in 1996, when peaks in Chl *a* migrated back upstream. Middle frame: mean annual loadings of total N (TN) and total P (TP) to the Neuse River Estuary. Lower Frame: freshwater discharge to the Neuse River Estuary measured at the U.S. Geological Survey gauging station (No. 02089500) located at Kinston, NC, approximately 20 km upstream from Streets Ferry. The hurricanes that have impacted the watershed since 1996 (Bertha and Fran (1996); Bonnie (1998); Dennis, Floyd, and Irene (1999); and Isabel (2003)) are indicated by symbols. Error bars represent standard error.

(1983 and 1985) exhibiting extreme summer droughts (*20*). In contrast, the post-1995 period witnessed a sudden and sustained increase in tropical storm and hurricane activity (*27*), possibly signaling an increase in Atlantic hurricane frequency (*28*). Since 1996, the NRE watershed has been affected by seven major hurricanes, the most extreme being Fran in July of 1996 and Dennis, Floyd, and Irene, which struck the region within a 6 week period during the fall of 1999. The latter hurricanes delivered over a meter of rainfall to parts of the watershed and caused catastrophic flooding (*27*). Most recently, the region was impacted by Hurricane Isabel in September 2003, following wet spring−summer months.

The floodwaters of late 1996 to early 1997 and 1999−2000 flushed phytoplankton accumulations out of the NRE into Pamlico Sound and prevented the formation of Chl *a* maxima (*27*). Once the flooding receded and water residence time increased, Chl *a* maxima and phytoplankton blooms re-established themselves at midestuarine locations (Figure 4). These blooms were largely controlled by N inputs to the NRE (*29*, *30*).

Upstream freshwater Chl *a* maxima or phytoplankton blooms have continued to be absent in the post-hurricane period. While these large hydrologic perturbations have introduced a significant amount of variability in the data sets shown in Figures 2−4, they apparently have not altered the long-term trend that seems to have followed the P-reduction strategy of the late 1980s, namely, peaks in phytoplankton production and resultant algal blooms.

The proposed downstream movement of the estuarine eutrophication gradient following selective upstream P reduction is conceptualized in Figure 5. Shown is the pre-P reduction period (1970s through mid-1980s) when both N and P loadings to the NRE increased (upper frame) followed by the post-P reduction period (late-1980s and onward), when P reductions were in place. The Chl *a* Max represents the zone of maximum phytoplankton productivity and bloom development in the estuary. In the 1970s through mid-1980s period, this zone was concentrated toward the upstream segment of the estuary, while following P reductions, this zone tended to migrate downstream. The period of increased hurricane activity, starting in the mid 1990s, is shown, as well as routes of N loss (sedimentation and denitrification) associated with the upstream algal N-filter mechanism.

Displacement of the eutrophication gradient downstream in response to increases in N/P loading appears to also have taken place in other estuarine systems experiencing intensive P but less so N reductions. These include (1) the Chesapeake Bay, MD/VA, where exclusive P removal in some of its tributaries (e.g., the Potomac River) was accompanied by increased N driven primary production in the downstream mesohaline mainstem of the estuary (*31*) and (2) the southern Sweden Baltic Sea archipelago region and associated fjords, where aggressive upstream P reductions greatly reduced freshwater algal production, while downstream N-limited mesohaline production remained unaffected or increased in places (*32*, *33*).

Nitrogen overenrichment, in addition to enhancing eutrophication, may induce other nutrient limitations in some estuarine and coastal waters. Most notable is the increased potential for silicon (as silicic acid, $Si(OH)_4$) limitation in coastal ecosystems such as the Northern Gulf of Mexico (Mississippi River plume) and the North Sea (*34*). In addition, enhanced N loading may lead to enhanced denitrification, thereby affecting the relationships between new N inputs, their transformations, and coastal N budgets.

Collectively, these results suggest that if we are to stem eutrophication along the freshwater−marine gradients typifying many of the world's estuaries, parallel N and P reductions may be needed. In many instances, N input reductions should probably take place starting in the upstream freshwater region as mandated by the Neuse River Basin TMDL, despite the fact that N may not be the limiting factor there. At the same time, P input restrictions should be maintained in this region, as there is ample evidence that upper estuarine algal blooms are frequently controlled by P availability (*13*, *19*, *23*). Overall, a larger-scale consideration of estuarine nutrient management is required where the freshwater and marine components are intimately connected from nutrient processing, cycling, and control perspectives. This argues for integrative approaches to watershed and estuarine nutrient management, where the effects and ramifications of nutrient inputs are considered along the entire freshwater−marine continuum. An example of successful system-wide dual nutrient management is the Patuxent Estuary (subestuary of Chesapeake Bay), where parallel N and P reductions have effectively reduced eutrophication throughout the entire length of the estuary (*35*).

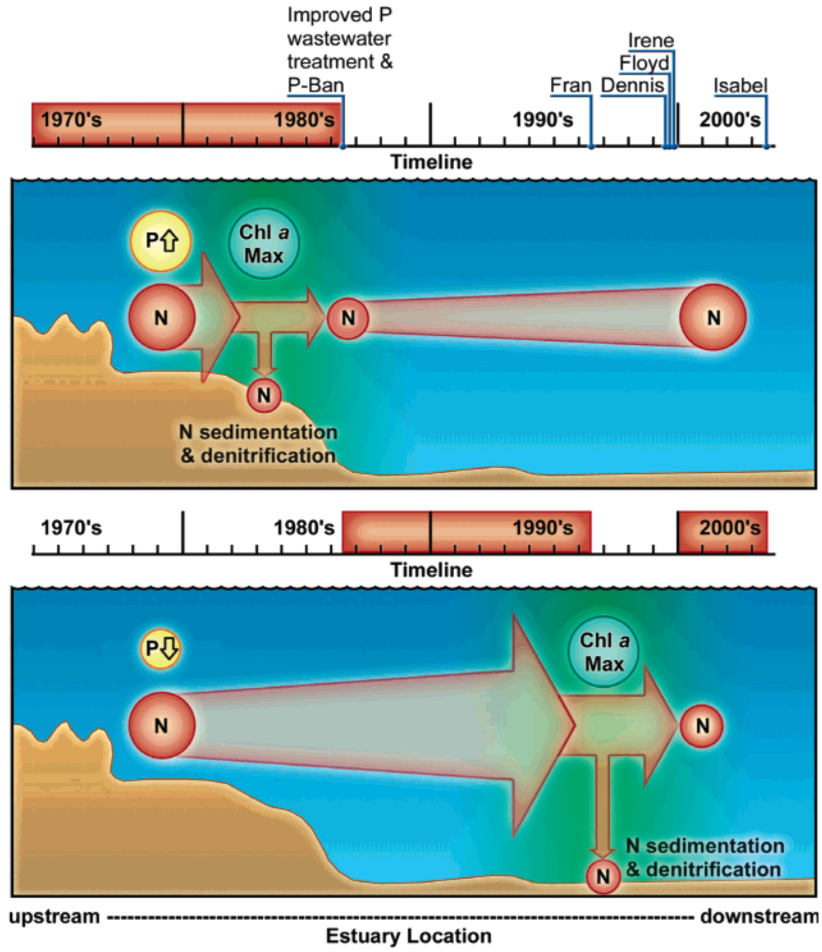

FIGURE 5. Conceptualization of pre- and post-P reduction impacts on the eutrophication dynamics of the Neuse River Estuary. Shown are the pre-P reduction period (upper frame) and the post-P reduction period (lower frame). The zone of maximum phytoplankton production and bloom formation (as chlorophyll *a*) is indicated as Chl *a* Max. Also shown are the major routes of N loss associated with the Chl *a* Max nutrient filter. Included are the times at which major hurricanes impacted the Neuse River Estuary Basin, signaling a period of elevated Atlantic hurricane activity that started in the mid-1990s.

Long-term (i.e., decadal) nutrient management strategies will also need to take climatic and hence hydrologic oscillations and resultant shifts in in-stream N and P processing into consideration. For example, estuaries may have greater tolerance for high nutrient loads when increased frequencies of tropical storms and hurricanes prevail. The elevated freshwater discharge resulting from these events will reduce residence time and minimize the potential for phytoplankton bloom formation, as well as in-stream N depuration processes, including denitrification and burial. Conversely, years having strong seasonality (i.e., wet winter−spring followed by dry summer−fall months) will lead to short but intense nutrient input pulses followed by periods of long residence time, ideal conditions for bloom formation and other negative manifestations of eutrophication. Thus, nutrient management should be highly adaptive, taking short- and longer-term patterns and trends, as well as a range of relevant scales into consideration.

Human perturbations of the major nutrient cycles have had profound impacts on aquatic production and biogeochemical cycling worldwide. These impacts have been apparent in freshwater ecosystems for several centuries, and the past 50 years have witnessed a concerted effort aimed at mitigating the undesirable effects of nutrient over-enrichment by P input controls. These efforts, however, have had unintentional yet profound effects on eutrophication dynamics of the further downstream N-limited estuarine and coastal waters, which have seen increasingly large N loads brought on by growing anthropogenic N inputs and a lack of control on freshwater N loading. Exclusive P limitation in upstream tributaries has reduced their N-filtering capacity, thereby exacerbating the eutrophication potential and potentially altering nutrient stoichiometry of many downstream estuarine and coastal waters, our greatest fisheries resources and major sites of global carbon, nutrient (N, P, Si, and Fe), and oxygen cycling.

Acknowledgments

Technical assistance was provided by J. Fear, B. Peierls, J. Sauber, and P. Wyrick. We appreciated critiques of this manuscript by R. Christian and J. Rudek. This work was supported by the National Science Foundation (DEB 9815495 and OCE 9905723), U.S. Department of Agriculture NRI Project 00-35101-9981, U.S. EPA STAR Projects R82-5243-010 and R82867701 and R83-0652, NOAA/North Carolina Sea Grant Program R/MER-43, and the North Carolina Department of Natural Resources and Community Development/UNC Water Resources Research Institute (Neuse River Estuary Monitoring and Modeling Project, ModMon).

Literature Cited

(1) Likens, G. E. *Limnol. Oceanogr. Spec. Symp.—Am. Soc. Limnol. Oceanogr.* **1972**, *No. 1*.
(2) Schindler, D. W. *Science* **1977**, *195*, 260−262.
(3) Vollenweider, R. A. *Mem. Ist. Ital. Idrobiol.* **1976**, *33*, 53−83.
(4) Smith, V. H. *Limnol. Oceanogr.* **1990**, *35*, 1852−1859.
(5) Edmondson, W. T. *Science* **1970**, *169*, 690−691.
(6) Ryther, J. H.; Dunstan, W. *Science* **1971**, *171*, 1008−1112.

(7) Nixon, S. W. *Ophelia* **1995**, *41*, 199−219.
(8) Smetacek, V.; Bathmann, U.; Nöthig, E.-M.; Scharek, R. In *Ocean Margin Processes in Global Change*; Mantoura, C. F., Martin, J.-M., Wollast, R., Eds.; John Wiley & Sons: Chichester, U.K., 1991; pp 251−279.
(9) Jørgensen, B. B.; Richardson, K. *Eutrophication of Coastal Marine Systems*; American Geophysical Union: Washington, DC, 1996.
(10) National Research Council (NRC). *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*; National Academy Press: Washington, DC, 2000.
(11) Peierls, B. L.; Caraco, N. F.; Pace, M. L.; Cole, J. J. *Nature* **1991**, *350*, 386−387.
(12) Boesch, D. F.; Burreson, E.; Dennison, W.; Houde, E.; Kemp, M.; Kennedy, V.; Newell, R.; Paynter, K.; Orth, R.; Ulanowicz, W. *Science* **2001**, *293*, 629−638.
(13) Conley, D. J. *Hydrobiologia* **2000**, *419*, 87−96.
(14) Vitousek, P. M.; Mooney, H. A.; Lubchenko, J.; Mellilo, J. M. *Science* **1997**, *277*, 1494−1497.
(15) Paerl, H. W. *Limnol. Oceanogr.* **1997**, *42*, 1154−1165.
(16) Diaz, R. J.; Rosenberg, R. *Oceanogr. Mar. Biol. Annu. Rev.* **1995**, *33*, 245−303.
(17) Rabalais, N. N.; Turner, R. E., Eds. *Coastal Hypoxia: Consequences for Living Resources and Ecosystems*; Coastal and Estuarine Studies 58, American Geophysical Union: Washington, DC, 2001.
(18) Copeland, B. J.; Gray, J. *Status and Trends Report of the Albemarle-Pamlico Estuary*; Steel J., Ed.; Albemarle-Pamlico Estuarine Study Report 90-01. NC Department of Environmental Health and Natural Resources: Raleigh, 1991.
(19) Paerl, H. W. *Factors Regulating Nuisance Blue-green Algal Bloom Potentials in the Lower Neuse River, NC*; University of North Carolina Water Resources Research Institute Report 188; 1983; p 48.
(20) Stow, C. A.; Bursuk, M. E.; Stanley, D. W. *Water Res.* **2001**, *35*, 1489−1496.
(21) Paerl, H. W.; Pinckney, J. L.; Fear, J. M.; Peierls, B. L. *Mar. Ecol. Prog. Ser.* **1998**, *166*, 17−25.
(22) Lenihan, H.; Peterson, C. H. *Ecol. Appl.* **1998**, *8*, 128−140.
(23) Paerl, H. W.; Mallin, M. A.; Donahue, C. A.; Go, M.; Peierls, B. L. *Nitrogen Loading Sources and Eutrophication of the Neuse River Estuary, NC: Direct and Indirect Roles of Atmospheric Deposition*; Report 291; UNC Water Resources Research Institute: Raleigh, NC, 1995; p 119.
(24) Pinckney, J. L.; Paerl, H. W.; Harrington, M. B.; Howe, K. E. Annual cycles of phytoplankton community structure and bloom dynamics in the Neuse River Estuary, NC (USA), *Mar. Biol.* **1998**, *131*, 371−382.
(25) Hobbie, J. E.; Smith, N. W. *Nutrients in the Neuse River Estuary, North Carolina*; Report UNC-SG-75-21; Sea Grant Program: Raleigh, NC, 1975; p 183.
(26) Rudek, J.; Paerl, H. W.; Mallin, M. A.; Bates, P. W. *Mar. Ecol. Prog. Ser.* **1991**, *75*, 133−142.
(27) Paerl, H. W., Bales, J. D.; Ausley, L. W.; Buzzelli, C. P.; Crowder, L. B.; Eby, L. A.; Fear, J. M.; Go, M.; Peierls, B. L.; Richardson, T. L.; Ramus, J. S. *Proc. Natl. Acad. Sci. U.S.A.* **2001**, *98*, 5655−5660.
(28) Goldenberg, S. B.; Landsea, C. W.; Mestas-Nunez, A. M.; Gray, W. M. *Science* **2001**, *293*, 474−479.
(29) Piehler, M. F.; Dyble, J.; Moisander, P. H.; Pinckney, J. L.; Paerl, H. W. *Aquat. Ecol.* **2002**, *36*, 371−385.
(30) Paerl, H. W.; Dyble, J.; Twomey, L.; Pinckney, J. L.; Nelson, J.; Kerkhof, L. *Antonie van Leeuwenhoek* **2002**, *81*, 487−507.
(31) Chesapeake Bay Program. *Response of the Chesapeake Bay Water Quality Model to Loading Scenarios*; Technical Report CBP/TRS 101/94; U.S. EPA Chesapeake Bay Program: Annapolis, MD, 1994.
(32) Brattberg, G. *Vatten* **1986**, *42*, 141−153.
(33) Elmgren, R.; Larsson, U. In *Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection*; Galloway, J., Cowling, E., Erisman, J. W., Wisniewski, J., Jordan, C., Eds.; A. A. Balkema Publishers: Lisse, The Netherlands, 2002; pp 371−377.
(34) Turner, R. E.; Qureshi, N.; Rabalais, N. N., Dortch, Q.; Justic, D.; Shaw, R. F.; Cope, J. *Proc. Natl. Acad. Sci. U.S.A.* **1998**, *95*, 13048−13051.
(35) D'Elia, C. F.; Boynton, W. R.; Sanders, J. G. *Estuaries* **2003**, *26*, 171−185.

Received for review November 6, 2003. Revised manuscript received March 10, 2004. Accepted March 23, 2004.

ES0352350