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Priority Topics for

Nutrient Pollution in Coastal Waters

An Integrated National Research Program for the United States

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Nutrient Pollution in Coastal Waters: Priority Topics for an Integrated National Research Program for the United States

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The priority research topics outlined in this report represent a strong consensus of the scientific community. Over the past decade, many reports and papers have stated research needs for better understanding the problem of nutrient pollution of coastal waters (NRC 1993a, 1993b, 1994, 1999, 2000, 2001; Nixon 1995; Jorgensen and Richardson 1996; Vitousek et al. 1997; Carpenter et al. 1998; CENR 2000; CRMSW 2000; Howarth et al. 2000; Conley 2000; Hobbie 2000; Valigura et al. 2000; Cloern 2001; Mitsch et al. 2001; Rabalais and Turner 2001; Cowling et al. 2001; Rabalais 2002). This report draws heavily on these identified needs - determined based on the views of both environmental managers and scientists - to develop the ensuing topics for priority research needed to protect against nutrient pollution and to rehabilitate degraded coastal waters of the United States.

An early draft of the report was refined with input from a workshop of 46 invited participants held in Woods Hole, Massachusetts, on May 30, 2002. Those participants (listed below and on the adjoining page) included a wide mix of both academic and government agency scientists with expertise in coastal systems, forested ecosystems, and agricultural systems. During July and August of 2002, a revised draft of the report was sent to several hundred additional scientists for comment. Over 50 of these responded, and this final draft reflects this further input from the interested scientific community.

Participants in the workshop held in Woods Hole, Massachusetts, on 30 May 2002, included:

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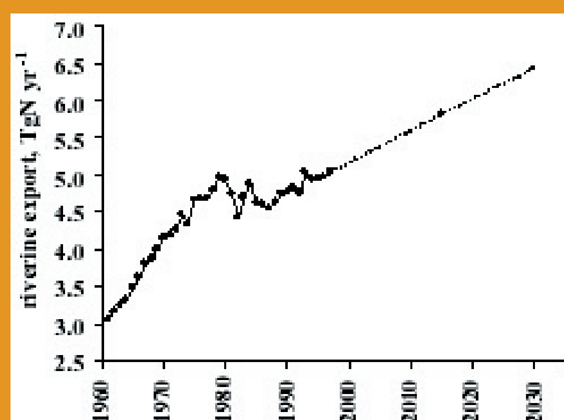
The past forty years have seen large increases in nutrient inputs to coastal waters as a result of population growth and greater production of food and energy. This has led to rapid and substantial changes to coastal ecosystems around the world (Boesch 2002). Within the United States, nutrients now pose the largest pollution threat to coastal waters (NRC 2000; Howarth et al. 2000), with an estimated two-thirds of coastal rivers and bays moderately to severely degraded from nutrient pollution (Bricker et al. 1999). Effects include increased areas of hypoxic and anoxic waters; alteration of food webs; degradation and loss of seagrass beds, kelp beds, and coral reefs; loss of biodiversity; and increased incidences and duration of harmful algal blooms. These changes provide significant additional challenges in protecting coastal waters not yet degraded and in restoring those that presently suffer from serious nutrient over-enrichment. In the *Clean Coastal Waters* report (NRC 2000), the National Academy of Sciences' Committee on Causes and Management of Coastal Eutrophication called for government officials to work with the scientific community, industry, and state and local jurisdictions to:

- Reduce the number of coastal water bodies demonstrating severe impacts of nutrient over-enrichment by at least 10% by 2010;
- Further reduce the number of coastal water bodies demonstrating severe impacts of nutrient over-enrichment by at least 25% by 2020; and
- Ensure that no coastal areas now ranked as 'healthy' develop symptoms related to nutrient over-enrichment in the future.

Changing Nutrient Loads

Both nitrogen and phosphorus contribute to nutrient pollution, but nitrogen is the more significant driver of eutrophication in most coastal areas in the United States. Human activity has increased the average flux of nitrogen to the coastal waters of the United States by some 4- to 5-fold, with several regions seeing increases as large as 10-fold (NRC 2000; Howarth et al. 2002). With population growth, land development, and the intensification of agricultural production, nitrogen loading is likely to continue to increase substantially in the future.



Estimated flux of nitrogen to coastal waters from the entire United States via rivers and sewage treatment plants. Future projections assume continued growth in export of cereal grains and population growth as predicted by the FAO and the US Census Bureau, respectively, and no major changes in diet, agricultural practices, or regulation of NOx emissions. (Reprinted from Howarth et al. 2002).

Research efforts to date have identified the general nature of coastal nutrient pollution in the United States and have led to an improved ability to identify sources of nutrient inputs. As a result, current knowledge is sufficient to begin to reverse the problem. Some active efforts are already under way to restore nutrient-degraded coastal waters in systems ranging from small lagoons to a large portion of the continental shelf of the Gulf of Mexico. It is across these scales that goals must be set and solutions applied. Science needs to be relevant for decisions made at these levels in order to meet the broader national objectives articulated by the *Clean Coastal Waters* report (NRC 2000).

Accordingly, an expanded and better integrated research program on coastal nutrient pollution should be a high national priority, in part, because further research can lead to more cost-effective and efficient control (NRC 2000). As one example, research can help identify what types of coastal ecosystems are most sensitive to nutrient enrichment so that abatement efforts can be most efficiently targeted. Further, research can lead to improved policies and technologies for reducing nutrient fluxes from the landscape. Research can also determine whether present patterns of nutrient-pollution effects and of sinks for nutrients in the landscape and in estuaries will persist or if the current situation is transient, as well as to whether problems from nutrient enrichment may continue to intensify even if nutrient sources come under better control. Research foci should be guided by knowledge requirements for defining achievable ecosystem health goals and with an eye toward how to achieve them most efficiently.

The focus of this report is to outline key research needs for better understanding and managing coastal nutrient pollution. Such research was identified as a high national priority by the *Clean Coastal Waters* report (NRC 2000). This Report also called for improved coastal monitoring and for a periodic and comprehensive national reassessment of the state of the Nation's coastal ecosystems in the context of the causes and consequences of nutrient pollution (NRC 2000). Such assessments are an essential component of the national effort to better manage nutrient pollution, and if conducted with suitable data, can provide progress reports on how well this problem is being addressed locally, regionally, and nationally. Recent assessments across the United States (Bricker et al. 1999; Heinz Center 2002; EPA 2002) have proven valuable, yet were handicapped by a lack of consistent, comprehensive observations, making comparisons among regions and particular ecosystems fairly uncertain (NRC 2000).

To improve the ability to assess changes in nutrient pollution, the Nation needs a comprehensive and sustained program to monitor the drivers and indicators of change. It should be noted that although many current monitoring efforts provide invaluable information for understanding coastal nutrient pollution, no national monitoring program has yet been designed and implemented specifically to address this problem. Within coastal marine ecosystems, most current monitoring is conducted by local or state agencies, and there is inadequate consistency across regions or the country. Improved monitoring for nutrient enrichment might be a logical part of the coastal component of the Global Ocean Observing System (GOOS). Within the landscape, the atmospheric deposition networks administered by EPA and NOAA should be expanded to more adequately measure nitrogen deposition in the full range of regions important in delivering nutrients to coastal systems.

Similarly, the USGS monitoring networks for stream and river discharge and nutrient fluxes should be maintained and expanded. Suggested improvements for a national monitoring network are described further in the NRC (2000) and in the Coastal Research and Monitoring Strategy Workgroup (2000). Guidelines for an international strategy for coastal monitoring are described by the Coastal Oceans Observations Panel of GOOS (ioc.unesco.org/goos/COOP.htm).

A coastal nutrient pollution research program should be viewed as complementary to current monitoring efforts and observing systems already in place or being developed, and to national assessments, benefiting from the data streams provided by these efforts. Equally, the research program can strengthen the scientific foundation of monitoring and assessment by providing for improved models and mechanistic insights that can enhance the interpretation of monitoring data. This can strengthen the connection of monitoring and observatory programs to the development of policies and management strategies for nutrient reduction. A research program at the national scale will also provide information that can aid in the evolution of the design of monitoring programs and observing systems to make them more effective tools for managing coastal nutrient pollution. To optimize the interaction between this research program and monitoring and assessment efforts, sites for intensive research should be included as sites within these monitoring networks. A solid integration of research, monitoring, and assessment can optimize the cost effectiveness of all.

Following are ten specific priority research topic areas that can increase the Nation's ability to understand and effectively manage the coastal nutrient pollution problem at both national and watershed or estuary scales.

Top 10 Priority Research Topics

I. Priorities for research **WITHIN** coastal ecosystems include:

1. Determination of the impact of nutrient pollution on societal goals for coastal ecosystems, and the relation of societal goals to measurable targets for management.
2. Development of approaches for assessing the sensitivity of diverse coastal systems to nutrient pollution.
3. Investigation of the ecological interactions among nutrient pollution, primary producers, and higher trophic levels (including fish and shellfish) in coastal systems.
4. Evaluation of alterations of biogeochemical cycles during eutrophication and during recovery from eutrophication.
5. Development of verified models for the quantitative forecasting of coastal system response to multiple stressors.

II. Priorities for research on the **DELIVERY** of nutrients **TO** coastal waters include:

6. Quantification of the inputs of nutrients to watersheds and determination of the fate of those nutrients under different land-use scenarios.
7. Analysis at the scale of watersheds of the role of groundwater, surface waters, riparian zones, and wetlands as sinks, sources, and transformers of nutrients.
8. Improvement of models of sources and fluxes of nutrients from the landscape under current and future conditions.
9. Development and evaluation of approaches and technologies to manage nutrient loadings to coastal systems.
10. Determination of the most effective policy and management approaches for reduction of nutrient delivery, and quantification of the costs, trade-offs, and benefits of controlling nutrient pollution from the landscape.

These identified fundamental research needs for an integrated national research plan for coastal nutrient pollution fall into two broad, but closely linked, categories:

1) Research relevant to the responses of coastal ecosystems to nutrient enrichment.

2) Research relevant to controlling the delivery of nutrients to these systems.

Each of these ten priority elements is described in more detail in the pages to follow. The report then concludes with a discussion of some additional considerations for developing an integrated national research program on nutrient pollution in coastal marine ecosystems.

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Priority #1.
Determination of the impact of nutrient pollution on societal goals for coastal ecosystems, and the relation of societal goals to measurable targets for management.

The degradation of coastal marine ecosystems by nutrient pollution is keenly felt by the public in many regions, and Society is increasingly striving to reverse coastal nutrient pollution. The restoration and protection of coastal ecosystems could be enhanced by a more clear definition of societal goals for these systems. In part, this entails a better understanding of how nutrient pollution affects the use and enjoyment of coastal ecosystems by Society. An even greater need is to translate what Society perceives as desirable into scientifically measurable goals that can serve as the basis of management.

In most coastal ecosystems, current efforts to control nutrient over-enrichment are based on standards for dissolved oxygen concentrations; in some locations, the area of bottom covered by seagrass beds is used as a basis for nutrient management. Are these approaches adequate to protect the values and utility of coastal ecosystems to Society? Or are fish and shellfish productivity lost at lower levels of nutrient enrichment, due to loss of habitat quality in seagrass and kelp beds or to alteration of ecological food-web structure? At what level does nutrient enrichment degrade aesthetic enjoyment of coastal systems, because of increased odors, lower water clarity, or increased incidences of harmful algal blooms? To what extent does Society value the loss of biodiversity that accompanies nutrient over-enrichment of coastal marine ecosystems?

A key need is to develop appropriate indicators of nutrient pollution that can be related to societal goals for protecting coastal ecosystems. Another need is to relate these indicators and goals to nutrient loads so that specific targets for nutrient reduction can be set. These can serve as the basis for applying the total maximum daily load (TMDL) approach, or other load-based management strategies.

Critical research needs to improve understanding of social impacts and to relate societal goals to measurable goals that can be used in management include:

- Better assessment of the ecological damage to fish and shellfish resources from nutrient over-enrichment, including damage resulting from degradation of habitat quality.
- Exploration of a broader range of environmental impacts as the basis for analysis of social and economic impacts, including potential impacts on biodiversity, on ecosystem goods and

services, and on aesthetic enjoyment of coastal systems.

- Assessment of the trajectory of change due to nutrient enrichment in coastal ecosystems, including changes in dissolved oxygen, seagrass and kelp beds, habitat quality, and community composition and food-web structure; and assessment of how scientifically measurable changes relate to the criteria most important to Society.
- Development of indicators of nutrient pollution that can be related to the goals for protection and restoration that are important to Society; the development of early warning indicators is particularly desirable.

Priority #2.
Development of approaches for assessing the sensitivity of diverse coastal systems to nutrient pollution.

Some coastal marine ecosystems are far more sensitive to the effects of nutrient pollution than others. For instance, comparable levels of nutrient inputs result in far greater eutrophication in Chesapeake Bay than in Delaware Bay or northern San Francisco Bay. The Hudson River estuary and Atchafalaya Bay receive much higher levels of nutrient inputs, yet have fewer problems from eutrophication than does Chesapeake Bay. Although much is known about what causes the observed differences in coastal system sensitivity to nutrient pollution, no general tools exist for assessing their sensitivity to nutrient pollution. The development of a formal methodology could greatly aid the management of eutrophication in coastal marine ecosystems. The greatest effort could then be put into restoring and protecting those coastal ecosystems that are most sensitive; nutrient inputs into less sensitive ecosystems would be a lower priority.

A variety of physical and biological attributes of a coastal ecosystem can dampen or amplify the response to nutrient pollution. These include tidal amplitude, water residence time, turbidity, the timing of nutrient inputs, mixing and depth of the photic zone, the significance of grazing on phytoplankton by both benthic fauna and zooplankton, and the abundance of seagrass beds, macro-algal beds, coral, and salt marshes. The relative importance of these factors is known in only a few ecosystems, and virtually nothing is known about the interactions of various physical and biological parameters that influence the sensitivity of a coastal system to nutrient over-enrichment.

The development of a sensitivity assessment methodology for coastal marine ecosystems requires information on:

- Dose-response curves for a variety of systems to nutrient enrichment.
- Integrated physical and biological descriptors, using standardized approaches for estimating various parameters, such as water residence time and ecological structure.
- The interaction of physical forcing functions and ecological structure in modulating the effects of nutrient enrichment, and how this may be influenced by climate change and variability.
- The role of nutrient enrichment as a factor in controlling dominance of ecological function by the benthos versus the plankton.
- How estuaries functioned before they were heavily enriched in nutrients by human activity.

Priority #3.
Investigation of the ecological interactions among nutrient pollution, primary producers, and higher trophic levels (including fish and shellfish) in coastal systems.

Nutrient enrichment can affect the structure of coastal marine ecosystems and the productivity of fisheries (often termed as bottom-up control), and conversely, the structure of the ecosystem can affect the response of the system to nutrient enrichment (top-down control). Our understanding of both of these effects is still quite limited. A better understanding of the bottom-up effects of nutrient enrichment is necessary for the estimation of the societal and economic costs of eutrophication. A better understanding of the top-down effects could lead to better management of nutrient pollution.

With regard to the bottom-up effects of nutrient enrichment, the "agricultural model" of Nixon (1995) suggests that greater nitrogen inputs to coastal marine ecosystems lead to greater rates of primary productivity and to greater productivity of fisheries. On the other hand, nutrient enrichment can lead to a variety of changes in function and structure that are detrimental to fishery production, including hypoxia and anoxia; degradation or loss of quality habitat, such as seagrass beds; and changes in phytoplankton community composition, leading to changes in trophic structure and energy flow. Accordingly, nutrient enrichment may result in greater fishery production up to a point, but further enrichment may lead to structural changes that lower fishery production. Caddy (1993) presented this argument in a qualitative way, focusing on fishery losses from anoxia, but the quantitative relationship between nutrient loading and these changes has been studied in very few, if any, coastal ecosystems. Many attempts to examine the effect of eutrophication on fishery productivity through analysis of historical fishery data have been confounded by the degree of noise in the data and by over-fishing of many stocks at the same time that nutrient loadings increased. The effects of nutrient enrichment on ecosystem structure and function and on fishery production may well vary among different types of coastal marine ecosystems.

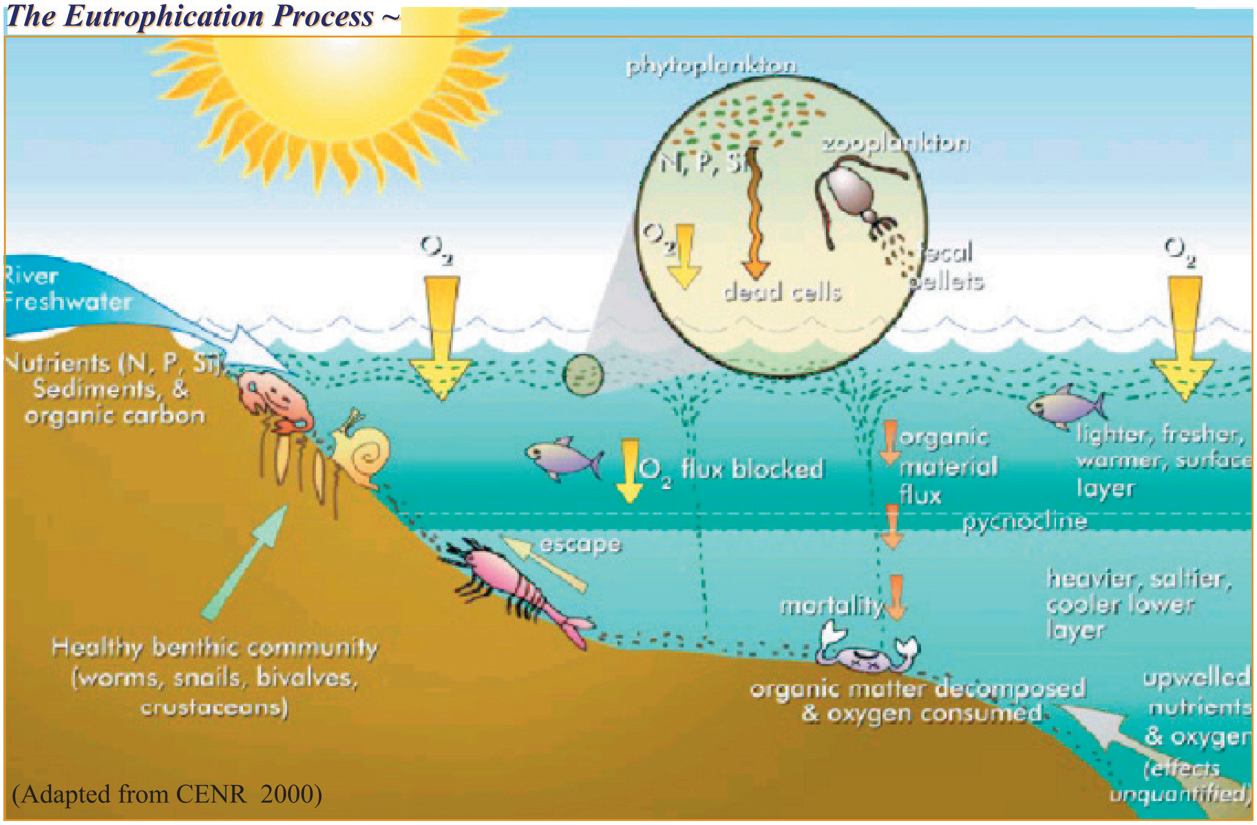

This crab could not survive in the anoxic zone near the mouth of the Mississippi River. Photo courtesy of Nancy Rabalais and the National Undersea Research Program.

Top-down effects of grazing by zooplankton and by benthic filter feeders have been shown to strongly influence phytoplankton abundance and productivity in lakes and has been invoked as a regulator of eutrophication in estuaries and coastal seas. Over-fishing can cause cascading effects on trophic structure, leading to changes in grazing by zooplankton. Degradation of benthic suspension feeding communities, such as oyster reefs and mussel beds, may aggravate eutrophication by reducing phytoplankton mortality; if so, restoration of such reefs and beds may be effective in lessening the influences of nutrient over-enrichment. However, the quantitative influences of these top-down effects as interacting factors with nutrient enrichment have been studied in very few coastal marine ecosystems.

Important questions to consider include:

- To what extent is ecological trophic structure altered during nutrient enrichment? Does nutrient enrichment lead to predictable changes in the composition of phytoplankton? benthic primary producers? Do these effects cascade up the food web?
- What are the relative influences of primary productivity and of trophic structure as regulators of fish and shellfish productivity? Are there predictable changes in the relative importance of these influences as nutrient enrichment increases?
- What is the quantitative importance to fishery recruitment and productivity of habitats that are sensitive to degradation during nutrient enrichment, such as seagrass beds and other benthic habitat?
- What is the importance of grazing, both by benthos and by zooplankton, in regulating phytoplankton biomass and productivity in coastal marine ecosystems, and how does this interact with physical controls on phytoplankton? To what extent can these top-down controls counteract the effects of nutrient enrichment?
- Does grazing interact with nutrient enrichment to influence composition of phytoplankton and of benthic primary producers? Does this have consequences for organic matter sedimentation and bottom water dissolved oxygen concentrations? For energy flow through the food web?
- How do the factors discussed above vary across different types of coastal marine ecosystems?
- What is the trajectory of recovery from nutrient over-enrichment?

The Eutrophication Process ~



(Adapted from CENR 2000)

Priority #4.
Evaluation of alterations of biogeochemical cycles during eutrophication and during recovery from eutrophication.

The sources and sinks of nitrogen, phosphorus, silica, and iron can be altered by eutrophication. For example, the adsorption of phosphorus onto both clastic sediments and tropical carbonate sediments may be lessened as ecosystems become more eutrophic. Bottom water anoxia may alter rates of denitrification, and whole-water column anoxia may favor planktonic nitrogen fixation. Eutrophication may increase iron availability as sediments become more reducing, but silica availability may decrease due to greater sedimentation and/or slower decomposition in sediments. These changes in biogeochemical cycles may result in positive or negative feedbacks on eutrophication, and may alter the phytoplankton community composition and favor harmful algal blooms. Further, changes in phytoplankton or zooplankton community composition that accompany nutrient enrichment can alter the rate of sedimentation of organic matter, and therefore the concentration of dissolved oxygen in bottom waters. A better understanding of how biogeochemical cycles change during eutrophication, and during the recovery from eutrophication, is essential for making sound policy and management decisions about protection and restoration.

Key questions to consider include:

- What changes does nutrient enrichment cause in the biogeochemical cycles within coastal marine ecosystems of elements, such as nitrogen, phosphorus, silica, and iron, and how may these changes provide positive or negative feedbacks to eutrophication? It is particularly important to understand how denitrification and nitrogen fixation are altered by eutrophication.
- How are changes induced from nutrient enrichment in biogeochemical cycles of nitrogen, phosphorus, carbon, silica, and iron related to salinity along an estuarine gradient, and how does this influence the sensitivity of a coastal marine ecosystem to nutrient pollution? How are these changes influenced by seasonal changes in salinity, and how might they respond to hydrologic changes associated with climate change and variability?
- Are the changes that occur during nutrient enrichment similar across classes of ecosystems, or do some types of coastal ecosystems respond differently than others due to differences in physical characteristics or ecological structure? What changes are associated with system changes from benthic to pelagic domination of primary production?
- Are there general changes during eutrophication in the nutrients that most limit production at either the annual or seasonal timescale? How might this effect the management of nutrient pollution in coastal systems?
- How readily reversible are the changes in biogeochemical cycles once nutrient loads are reduced?
- How do changes in biogeochemical cycles influence phytoplankton composition and harmful algal blooms, especially with respect to changing stoichiometry and altered availability of silica, iron, and other nutrients?

Priority #5.
Development of verified models for the quantitative forecasting of coastal system response to multiple stressors.

With regard to understanding nutrient over-enrichment, the "development of process models for estuaries and open coastal systems is still in its infancy" (NRC 2000). Most models for the management of eutrophication are site specific, and while often relatively sophisticated with regard to hydrology, they generally are quite simplistic in their portrayal of ecological and biogeochemical functions and feedbacks. Yet, extensive research and monitoring data exist, in various forms, which could be used to improve the general applicability of such models. The development of more ecologically and biogeochemically sophisticated models, and models that are general enough to be applicable to a range of coastal ecosystems, could serve to integrate scientific understanding of nutrient enrichment and to highlight key uncertainties. Such models would also aid managers in setting goals for protecting and restoring coastal marine ecosystems from nutrient over-enrichment. More sophisticated process-based models are also essential for a better understanding of how nutrient pollution interacts with other stressors, including toxic substances, habitat loss, hydrologic alterations, over-fishing, invasive species, and climate change. Agencies should encourage a variety of modeling approaches, since the best course of action for the development of eutrophication models remains quite unclear.

Factors to consider in developing, verifying, and using such models include:

- Models need to balance adequate representation of physical, ecological, and biogeochemical processes with the benefits of simplicity and the dangers of over-parameterizing a model.
- There is a need to develop models that include both bottom-up and top-down interactions of primary producers with higher trophic levels.
- There is a need to develop models that include biogeochemical feedbacks that occur during nutrient enrichment, including changes in organic sedimentation, phosphorus adsorption, denitrification, nitrogen fixation, and silica sedimentation.
- There is a need to develop models that are responsive to climate change and variability.
- To the extent possible, models should include explicit characterization of uncertainty.
- Models should be validated with data independent of that used in their development and calibration.
- Agencies should fund the development of databases that can be used to calibrate and verify process models and that can be used to develop statistical models.

Priority #6.
Quantification of the inputs of nutrients to watersheds, and determination of the fate of those nutrients under different land-use scenarios.

The identification of nutrient sources is critical to managing the problem of nutrient pollution of receiving water bodies. Despite major progress over the past decade, much uncertainty still exists in estimating the sources of nutrients that are transported from watersheds to coastal ecosystems. Key causes of this uncertainty are incomplete or inaccurate knowledge on the inputs of nutrients to the landscape and poor understanding of the fate of nutrients within the landscape, particularly for nitrogen. For the coastal United States as a whole, and in most individual estuaries, nonpoint sources of nutrients are larger than inputs from sewage and other point sources, and our knowledge on these nonpoint sources is particularly poor. However, even urban point sources of nutrients and their fate are poorly known for many coastal ecosystems. While there is an urgent need to better understand sources and fate of nutrients from agricultural systems, forests, and other land uses, the need for improved knowledge of nutrient sources in mixed-land-use types is particularly acute.

Dense bloom of blue-green algae in the Potomac River downstream of a farm field. Photo courtesy of W. Bennett, U.S. Geological Survey.

On average, only a relatively small fraction (20 to 25 percent) of nitrogen inputs to large watersheds is exported downstream in rivers, with the amount in any given year highly dependent on weather. The rest is stored in soils and biomass or converted to gaseous forms of nitrogen through the process of denitrification. Much of the denitrification in the landscape probably occurs in surface waters, wetlands, and riparian zones (see Priority #7 to follow), but denitrification may be equally important, or even greater, in soils, at least in humid regions (van Breemen et al. 2002). Denitrification in agricultural soils has not been sufficiently studied, but denitrification may be an important sink for nitrogen in such soils, particularly when they are wet. A better understanding of these nitrogen sinks in the landscape is vital to better management of nutrient fate and transport, so that future changes can be anticipated. For instance, the accumulation of nitrogen in soil may slow over time as this sink saturates, resulting in more downstream export of nitrogen. Also, denitrification in soils may increase or decrease in the future as climate change alters soil moisture.

Atmospheric deposition of nitrogen, and particularly deposition onto the terrestrial landscape with subsequent export downstream, remains the most poorly quantified input of nitrogen to coastal marine ecosystems (NRC 2000). For some coastal marine ecosystems with relatively little agriculture in their watersheds, deposition is clearly the largest input of nitrogen, while deposition is a minor source where agricultural activity and fertilizer application in the watershed is more intense. However, for many systems estimates of the importance of atmospheric deposition as an input of nitrogen are quite divergent, including even some well-studied estuaries, such as Chesapeake Bay and the Hudson River estuary. Uncertainties in both the rate and fate of deposition onto the landscape contribute to the divergence of these estimates. Networks for atmospheric deposition have been biased against sampling in coastal areas and near urban and agricultural sources of air pollution, exacerbating these uncertainties. Few, if any, atmospheric deposition networks measure organic nitrogen or dry deposition of ammonia.

Recent research in small forested catchments suggests that the details of disturbance and land-use history are critically important in determining how much nitrogen from deposition is retained in a forest or denitrified versus exported downstream (Goodale et al. 2000; Lovett et al. 2000); approaches are needed for evaluating the fate of deposition in forests at larger spatial scales (such as multiple catchments across a region or large watershed). Virtually nothing is known about the fate of nitrogen deposition in suburban areas or landscapes with mixed land-uses.

Terrestrial ecosystems vary in the effectiveness with which they retain nutrients. Research could lead to a ranking of terrestrial systems with regard to their potential to export nutrients to downstream ecosystems and with regard to how climate variability and land-use changes may alter this export.

Important research needs include:

- Measurement of denitrification in terrestrial ecosystems, particularly in agricultural soils, and determination of how this process relates to land use and management (particularly agricultural practices).
- Better estimation of nitrogen deposition in coastal areas and close to emission sources for NOx (particularly from mobile sources, since deposition can be high near ground-level sources) and for NHx (particularly from animal wastes).
- Improved estimation of dry deposition of both oxidized and reduced forms of nitrogen, particularly near emission sources.
- Analysis of organic nitrogen fluxes, including sources of organic nitrogen in deposition, and storage in, and export of, organic nitrogen from terrestrial ecosystems.
- Effects of disturbance history in terrestrial ecosystems, and analysis of nitrogen retention and export in catchments at a variety of scales.
- Fate of nitrogen deposition in urban, suburban, and mixed-land-use areas.
- Analysis of the time trajectory of nitrogen accumulation from atmospheric deposition in the landscape, and how climate change and variability may influence nitrogen storage and downstream export.
- Improved estimates of atmospheric and groundwater fluxes, in addition to surface runoff, of nutrients from agricultural systems.
- Complete mass balance of nutrients in urban landscapes, in agricultural fields, and in animal-feeding operations, including all major sources, sinks, and storage terms.

Priority #7.
Analysis at the scale of watersheds of the role of groundwater, surface waters, riparian zones, and wetlands as sinks, sources, and transformers of nutrients.

As noted under Priority #6, most of the nitrogen mobilized by human activity in the landscape is not exported to coastal ecosystems, but rather is either denitrified or stored in the landscape (NRC 2000). In general, the relative importance of denitrification in comparison with storage of nitrogen in soils, vegetation, and accumulation in groundwater is poorly known, although both denitrification and storage are clearly important. The relative importance of the two processes may vary among regions due to differences in climate, topography, land management, soil, or groundwater hydrology. For many watersheds, available data on nitrogen sources and sinks suggest that roughly half of the net nitrogen inputs from human activity may be denitrified, with a significant amount of this occurring in wetlands and surface waters (van Breemen et al. 2002).

Many studies have shown that riparian zones and wetlands are major sinks for nitrate, with much of the nitrate probably being denitrified. Fewer studies have examined all inputs and outputs of nitrogen to riparian zones and wetlands, including fluxes of organic nitrogen. Denitrification also occurs readily in streams and river beds, in lakes, and in groundwater aquifers. However, the cumulative effect of this process across systems at the scale of the landscape is very poorly estimated. Further research on the fate of nitrogen in wetlands, surface waters, and groundwater is necessary for the best management of coastal nutrient pollution. This research should be conducted in the context of whole watersheds.

Key research needs include:

- Analysis of all forms of nitrogen in hydrologic fluxes through wetland, riparian zone, and surface-water ecosystems.
- Estimation of the efficiency of riparian zones, wetlands, surface waters (particularly first-order streams), and groundwater as sinks of nitrogen through denitrification at the scale of large watersheds and landscapes.
- Determination of the importance of temporal patterns in fluxes (such as seasonality) in controlling sinks for nutrients in the landscape, and how this might vary depending on climate, topography, and size of watersheds.
- Analysis of the rate of accumulation of reactive nitrogen in aquifers as a temporary sink of nitrogen in the landscape, and quantification of the rate and time frame over which nitrogen might be re-injected to surface waters.
- Measurement of the production of N_2O during denitrification in different types of ecosystems, and development of possible approaches for reducing the amount of N_2O released to the atmosphere.

Priority #8.
Improvements of models of sources and fluxes of nutrients from the landscape under current and future conditions.

Many models exist for estimating sources and fluxes of nutrient inputs to watersheds and coastal ecosystems, and these are critical tools for the manager charged with improving water quality. However, many of these models have not been validated or verified with independent data, and the application of different models to the same watershed can yield very different estimates of nutrient sources and fluxes. Many models do not include all major inputs of nitrogen to the landscape, with many ignoring the importance of atmospheric deposition. Few address inputs from livestock and poultry production operations. Most current models do not include sinks of nitrogen in wetlands, riparian zones, and in surface waters. And very few models are responsive to changes in management practices. Improving the models available to managers is a critical element in efforts to most efficiently reduce nutrient pollution in coastal marine ecosystems.

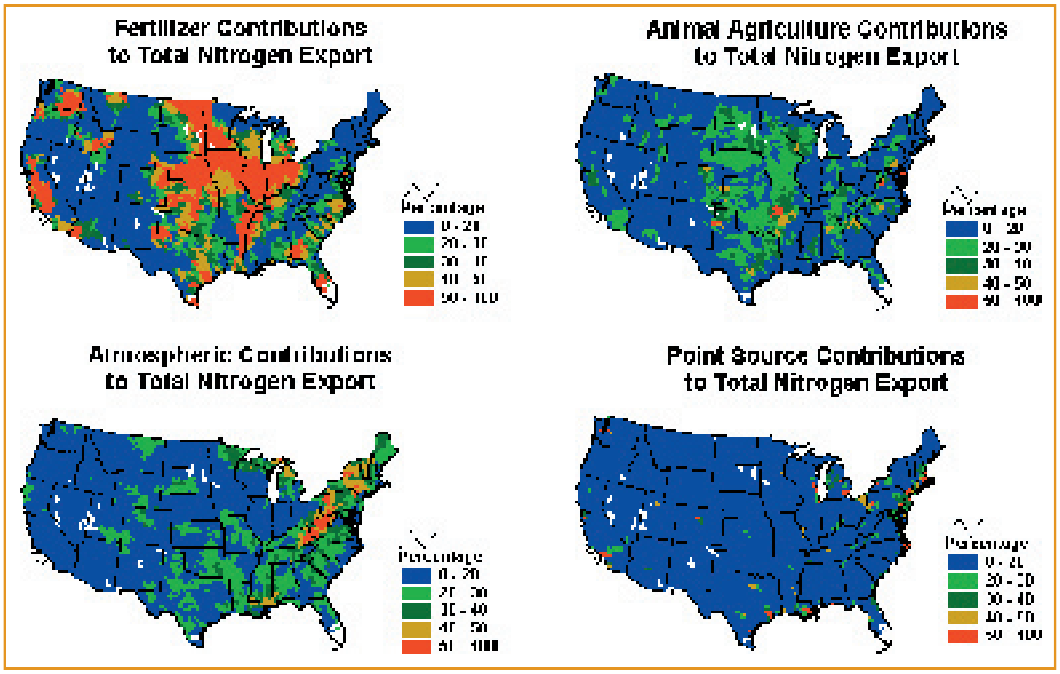
Some models have been developed for relatively small spatial scales, while others have been developed for large watersheds or regions. To date, there have been few, if any, efforts to compare these models across scales. Source modeling is also hampered by the data available for assessing nitrogen inputs across the Nation in a consistent manner. A nationally consistent database of nitrogen use in the landscape, both purposeful (such as in agriculture) and inadvertent (such as from fossil-fuel combustion), would be extremely helpful in developing improved models for estimating nitrogen fluxes to coastal ecosystems. The goal of the modeling research should be to develop a comprehensive, quantitative understanding of nitrogen cycling and transport in the landscape of large river basins and in smaller watersheds that deliver nitrogen to sensitive coastal ecosystems.

Key considerations for model improvements include:

- Testing models through hindcasting, as well as using them to forecast.
- Validating models with data independent of that used in their development and calibration.
- Including all major nitrogen sources, fluxes, and sinks.
- Making models responsive to land-use and management practices, and developing appropriate databases for the efficacy of management practices against which models can be calibrated and validated.
- Making models responsive to climate change and variability.
- Comparing models developed for different spatial scales.
- Developing an accurate and consistent set of data on nutrient inputs to regions, which can be used to drive models of export to coastal ecosystems.
- Developing a spatially explicit, georeferenced database that relates agricultural lands and practices that could drive models on nitrogen losses from agricultural fields. This should include information on soils, weather, and management practices and strategies, including crop types and nitrogen fertilizer application.

Priority #9.
Development and evaluation of approaches and technologies to manage nutrient loadings to coastal systems.

A variety of approaches exist for reducing nutrient loadings to coastal marine ecosystems. These include best management practices for farms and for construction projects, technologies for human and animal waste disposal, for urban runoff, and for removal of NOx from power plants and mobile emission sources, and designs for alternative energy sources that do not produce NOx and for creation of wetlands as sinks for nutrients in the environment. However, even better approaches could be developed, especially with regard to nitrogen. Many treatment technologies and management practices were designed to address phosphorus pollution; since nitrogen is more mobile in both groundwater and the atmosphere, these practices and technologies often need to be refined or altered. Also, there is an urgent need for independent evaluation of various



Percentage contribution from fertilizer, animal agriculture, atmospheric deposition, and point sources to the total nitrogen export from 2057 hydrologic units. (Smith and Alexander 2000)

practices, approaches, and technologies.

For the United States as a whole, agriculture is the largest source of nitrogen pollution to coastal waters (Howarth et al. 2002), although its contribution to individual coastal ecosystems varies greatly (NRC 2000). Both losses to surface and groundwater from agricultural fields and emissions from animal manures are major contributors of nitrogen pollution. Research could result in better management practices for reducing nutrient export from these sources. Pertinent research topics include biological N fixation, in-field denitrification, other factors regulating availability of soil nutrients to agricultural crops, site-specific techniques to improve the efficiency of use of nutrients in fertilizer and manure applications, and the relationship of fertilizer application rates and timing to losses of nutrients to surface waters in different settings. Important issues to consider are the type of crops grown, the use of cover crops, changes in soil organic matter, subsurface drainage, and type of tillage. Much of this research can be conducted at the scale of small agricultural plots, but methods are needed for scaling the results to individual fields and watersheds, including reasonably large watersheds with mixed land use. The influence of climate change and variability on fluxes of nutrients from agricultural systems also needs specific study.

Research on new approaches for nitrogen removal from wastewater streams should be encouraged. Although technologies certainly exist and are increasingly being used to reduce nitrogen loads from municipal treatment plants, there has been relatively little innovation in developing even better technologies (NRC 1993b). Perhaps of even greater importance are septic systems at individual homes, which are used to treat human wastes in many coastal areas. In general, these systems are poor at removing nitrogen, and septic wastes are a major source of nutrient pollution to many coastal ecosystems. Research on innovative technologies, and independent assessment of them, is highly desirable.

Under the Clean Air Act, control of nitrogen emissions from power plants and mobile sources (both on-road and off-road) has concentrated on lowering smog and ozone levels. This places an emphasis on reducing only oxidized nitrogen emissions and only during the summer. To adequately address the additional concern of coastal nutrient pollution, research is needed on approaches, strategies, and technologies for reducing emissions of all nitrogen compounds (including ammonia) to the atmosphere and throughout the year.

Constructed wetlands may play an increasingly important role in the future for wastewater treatment and for reducing nitrogen pollution from agricultural sources and from atmospheric deposition. Research should focus on the evaluation of the effectiveness of these systems, and on approaches for increasing their effectiveness as sinks for nutrients. For example, rather little is known about how the location of wetlands within a watershed affects their effectiveness in reducing nutrient fluxes, or the time frame over which they may remain effective.

Important research needs include:

- Development of management practices for reducing nitrogen losses from animal manures to groundwater and to the atmosphere in reactive forms, such as ammonia.
- Analysis of management practices for reducing loss of nutrients from agricultural fields in the context of soil, climate, slope, and agricultural practices, and development of a general classification scheme for leakiness of agricultural fields and the responsiveness to management, including cropping, tillage practices, and drainage.
- Development of fertilizer application technologies to increase efficiency of use and reduce losses to the environment.
- Evaluation of management practices and systems for reducing nitrogen loss at the scale of watersheds, particularly for watersheds with mixed land uses and in urban and suburban areas.
- Development of new treatment technologies for removing nitrogen from human waste streams at the scale of large sewage systems, small neighborhoods, and individual homes.
- Evaluation of alternative energy and transportation strategies as mechanisms for reducing atmospheric deposition of nitrogen.
- Development of wetlands as treatment systems for nitrogen in human and animal wastes and for increasing nitrogen removal from upstream watersheds.
- Independent assessment of the effectiveness of various management practices and technologies for reducing nutrient pollution.
- Determination of the limits of technology for nutrient control.

Excess nutrients can over-stimulate the growth of nuisance algal blooms. Photo courtesy of Puget Sound Water Quality Action Team.

Priority #10.
Determination of the most effective policy and management approaches for reduction of nutrient delivery, and quantification of the costs, trade-offs, and benefits of controlling nutrient pollution from the landscape.

Nutrients come from many sources in the landscape; a variety of approaches are possible for reducing these sources. These include voluntary approaches based on education and good citizenship, subsidies and financial incentives, or fear of regulation, in addition to technology-based regulation, fees or taxes that are based on permissible loading levels, and marketable permits for achieving permissible loading levels. Incentives can also be used to create or restore wetlands and riparian buffers as a mechanism to reduce nutrient fluxes to coastal ecosystems. The best approach may be a hybrid, using different strategies for different sources of nutrients in different settings, but more knowledge is needed on how to best target the various potential approaches to specific problems. Management decisions should be driven by the best available research on the relative efficacy of these various policy options. To the extent that management relies on economic approaches, better estimates of the costs for reducing nutrient fluxes from a variety of possible sources (and using a variety of techniques) are required.

Key questions to consider include:

- In addition to reducing nutrient pollution to coastal ecosystems, what ancillary benefits or detriments to Society or the environment accrue from various management options, and how can such benefits and detriments best be documented and measured?
- What cultural, legal, regulatory, or economic impediments exist for various management and policy options?
- What opportunities exist for reducing nitrogen pollution by altering societal behaviors, such as diet?
- Can optimization procedures be developed to explore the application of complex, hybrid policy approaches for reducing nutrient pollution?
- How might future changes in agricultural policies, technologies, or international agricultural markets affect policies for reducing nutrient pollution from agroecosystems?
- How might future changes in energy policy interact with policies for reducing nutrient pollution from agriculture and fossil-fuel combustion?

Additional Considerations ~ Selection of Research Sites.

Much of the research described above, such as that under Priorities #3 and #4, is site-specific. This research can be most efficiently conducted and new knowledge can be maximized if the research is focused on a set of index sites. For research in coastal ecosystems, these sites should be chosen to represent a range in sensitivity to nutrient pollution and to represent the diversity of coastal marine ecosystems in the United States. The NSF-funded Long-Term Ecological Research (LTER) sites provide a solid start toward an appropriate network and a model of how research might be conducted. However, current LTER sites in coastal ecosystems were established without consideration of how representative the sites are regarding sensitivity to nutrient enrichment. An additional set of LTER-like sites should be chosen to more completely represent the variety of coastal marine ecosystems that occur in the country, with an effort to include systems that vary in their sensitivity to nutrient pollution based on different physical, ecological, and watershed land-use characteristics. The selection criteria for these new LTER-like sites should include representation across a range of sizes. Including sites that have a well-established nutrient management structure already in place, such as some of the National Estuary Program and the National Estuarine Research Reserve sites, is also desirable, as the linkage between new scientific knowledge and application to management would be enhanced. Sites should include some with significant nutrient enrichment and some in which nutrient inputs are low.

For site-based research in the terrestrial landscape, current research sites can fill some, but not all, of the need. For instance, some of the work on nitrogen retention and loss in forests, grasslands, cropping systems, and urban areas can be conducted at current LTER sites, but to encompass an adequate range of soils, climates, nitrogen deposition rates, and management and disturbance histories, other sites are also needed. Agricultural experiment stations provide excellent sites for research on nutrient dynamics and losses from agricultural fields. However, a broadening or extension of these sites may be necessary to study nutrient losses from agricultural activity at the scale of watersheds. Research on nutrient loss from watersheds with mixed land use, and research on scale-dependent nutrient sinks in wetlands, riparian zones, and surface waters, is not adequately served by current research sites, such as those in the LTER network, alone. As discussed above for coastal marine ecosystems, the research agenda is best served by focusing on a relatively small number of intensively studied sites that are carefully chosen to represent a range of important system attributes. Support for this expansion of sites is required.

For both the coastal marine and terrestrial sites, cross-system comparisons should be encouraged. The synthesis of site-specific information into a more general framework, closely linked to the management agenda, can lead to a unique advancement of our understanding of coastal nutrient pollution. The goal is to more effectively and efficiently manage this major national problem.

Additional Considerations ~ Consistency of Methods and Availability of Data Sets.

Consistent approaches for data acquisition across systems should be an important component of a national research program for coastal nutrient pollution. Past efforts to understand the nature and scale of coastal nutrient pollution in the United Sates have been hampered by the use of different methods and techniques for measurement in different coastal ecosystems.

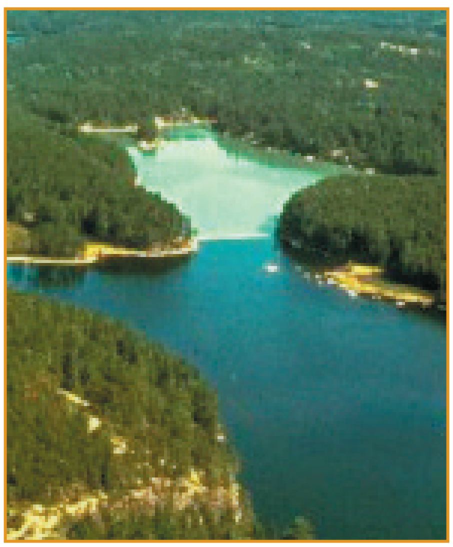
A national research program would also greatly benefit from having readily accessible compilations of data, including data from the intensive research sites, as well as from monitoring programs. Such data sets are extremely useful in developing, calibrating, and testing models (Priorities #5 and #9) and will be critical in developing a classification scheme for the sensitivity of coastal marine ecosystems to nutrient pollution (Priority #2). To optimize the usefulness of data compilations, quality control and consistency of measurement (including the data from monitoring programs) are critical.

Funding specifically designated for research based on the analysis of nationally available compilations of data is an important aspect of an integrated national research program for understanding coastal nutrient pollution.

Additional Considerations ~ A Call for Experimentation.

Perhaps the single most powerful tool for understanding eutrophication in lakes has been the use of whole-lake experiments, such as those conducted in the Experimental Lakes Area of Canada since the late 1960s. These experiments, in which lakes were enriched with phosphorus, carbon, and nitrogen alone, and in combination, have shown unequivocally that phosphorus is the primary nutrient causing eutrophication in most freshwaters. Whole-lake experiments have also demonstrated the importance of top-down, cascading controls on eutrophication and have helped to elucidate consequences and ecological and biogeochemical feedbacks that occur during eutrophication.

Such approaches could prove equally powerful in understanding nitrogen enrichment and its effects in coastal marine ecosystems, as has been demonstrated with a series of experiments with altered sewage discharges over a period of many years into an estuary in Sweden (the Himmerfjorden south of Stockholm; see NRC 2000). These experiments should be encouraged and funded in some coastal systems within the United States as an extremely cost-effective way to improve the knowledge base for better management of coastal eutrophication.



Additions of small amounts of phosphorus to one Experimental Lake Area (ELA) of Canada caused surface blooms of blue-green algae, illustrating the importance of phosphate as a cause of excessive algal growth (eutrophication). This experiment spurred legislation controlling the input of phosphorus to many water bodies. Photo courtesy of University of Manitoba, ELA Research Unit.

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