# Marine Science Review – 190

## Nutrient pollution

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In this review:



## A. Recent articles with abstracts

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Huang, Q., Shen, H., Wang, Z., Liu, X., and Fu, R. **Influences of natural and anthropogenic processes on the nitrogen and phosphorus fluxes of the Yangtze Estuary, China.** *Regional Environmental Change* 6(3): 125-131, 2006.

**Notes**: Nutrient flux to the sea through the estuary is important to the health of the sea. Combining natural processes with anthropogenic activities, we discuss the influence on the nitrogen and phosphorus fluxes to the Yangtze River basin, to the estuary and to the sea. The fluxes of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) to the estuary through the river/estuary interface are obviously higher than those to the sea through to the estuary/sea interface of the Yangtze estuary. The changes in nutrient fluxes through different interfaces are largely due to the estuarine hydrological and biogeochemical processes. Household, livestock and agricultural runoff are major sources of nitrogen from human activities, and household and livestock contribute to an increase in the anthropogenic phosphorus. The fluxes of DIN and DIP from economic activities account for about one-third of DIN and DIP fluxes to the sea through the Yangtze estuary.

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Greening, H. and Janicki, A. **Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA.** *Environmental Management* 38(2): 163-178, 2006.

**Notes**: Coastal waters have been significantly influenced by increased inputs of nutrients that have accompanied population growth in adjacent drainage basins. In Tampa Bay, Florida, USA, the population has quadrupled since 1950. By the late 1970s, eutrophic conditions including phytoplankton and macroalgal blooms and seagrass losses were evident. The focus of improving Tampa Bay is centered on obtaining sufficient water quality necessary for restoring seagrass habitat, estimated to have been 16,400 ha in 1950 but reduced to 8800 ha by 1982. To address these problems, targets for nutrient load reductions along with seagrass restoration goals were developed and actions were implemented to reach adopted targets. Empirical regression models were developed to determine relationships between chlorophyll *a* concentrations and light attenuation adequate for sustainable seagrass growth. Additional empirical relationships between nitrogen loading and chlorophyll *a* concentrations were developed to determine how Tampa Bay responds to changes in loads. Data show that when nitrogen load reduction and chlorophyll *a* targets are met, seagrass cover increases. After nitrogen load reductions and maintenance of chlorophyll *a* at target levels, seagrass acreage has increased 25% since 1982, although more than 5000 ha of seagrass still require recovery. The cooperation of scientists, managers, and decision makers participating in the Tampa Bay Estuary Program's Nitrogen Management Strategy allows the Tampa Bay estuary to continue to show progress towards reversing many of the problems that once plagued its waters. These results also highlight the importance of a multi-entity watershed management process in maintaining progress towards science-based natural resource goals.

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Camargo, J.A. and Alonso, A. **Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment.** *Environment International* 32(6): 831-849, 2006.

**Notes**: We provide a global assessment, with detailed multi-scale data, of the ecological and toxicological effects generated by inorganic nitrogen pollution in aquatic ecosystems. Our synthesis of the published scientific literature shows three major

environmental problems: (1) it can increase the concentration of hydrogen ions in freshwater ecosystems without much acid-neutralizing capacity, resulting in acidification of those systems; (2) it can stimulate or enhance the development, maintenance and proliferation of primary producers, resulting in eutrophication of aquatic ecosystems; (3) it can reach toxic levels that impair the ability of aquatic animals to survive, grow and reproduce. Inorganic nitrogen pollution of ground and surface waters can also induce adverse effects on human health and economy. Because reductions in $SO_2$ emissions have reduced the atmospheric deposition of $H_2SO_4$ across large portions of North America and Europe, while emissions of NOx have gone unchecked, $HNO_3$ is now playing an increasing role in the acidification of freshwater ecosystems. This acidification process has caused several adverse effects on primary and secondary producers, with significant biotic impoverishments, particularly concerning invertebrates and fishes, in many atmospherically acidified lakes and streams. The cultural eutrophication of freshwater, estuarine, and coastal marine ecosystems can cause ecological and toxicological effects that are either directly or indirectly related to the proliferation of primary producers. Extensive kills of both invertebrates and fishes are probably the most dramatic manifestation of hypoxia (or anoxia) in eutrophic and hypereutrophic aquatic ecosystems with low water turnover rates. The decline in dissolved oxygen concentrations can also promote the formation of reduced compounds, such as hydrogen sulphide, resulting in higher adverse (toxic) effects on aquatic animals. Additionally, the occurrence of toxic algae can significantly contribute to the extensive kills of aquatic animals. Cyanobacteria, dinoflagellates and diatoms may be stimulated by inorganic nitrogen pollution. Among the different inorganic nitrogenous compounds ($NH_4^+$, $NH_3$, $NO_2^-$, $HNO_2$, $NO_3^-$) that aquatic animals can take up directly from the ambient water, unionized ammonia is the most toxic, while ammonium and nitrate ions are the least toxic. In general, seawater animals seem to be more tolerant to the toxicity of inorganic nitrogenous compounds than freshwater animals, probably because of the ameliorating effect of water salinity (sodium, chloride, calcium and other ions) on the tolerance of aquatic animals. Ingested nitrites and nitrates from polluted drinking waters can induce methemoglobinemia in humans, particularly in young infants, by blocking the oxygen-carrying capacity of hemoglobin. Ingested nitrites and nitrates also have a potential role in developing cancers of the digestive tract through their contribution to the formation of nitrosamines. In addition, some scientific evidences suggest that ingested nitrites and nitrates might result in mutagenicity, teratogenicity and birth defects, contribute to the risks of non-Hodgkin's lymphoma and bladder and ovarian cancers, play a role in the etiology of insulin-dependent diabetes mellitus and in the development of thyroid hypertrophy, or cause spontaneous abortions and respiratory tract infections. Indirect health hazards can occur as a consequence of algal toxins, causing nausea, vomiting, diarrhoea, pneumonia, gastroenteritis, hepatoenteritis, muscular cramps, and several poisoning syndromes (paralytic shellfish poisoning, neurotoxic shellfish poisoning, amnesic shellfish poisoning). Other indirect health hazards can also come from the potential relationship between inorganic nitrogen pollution and human infectious diseases (malaria, cholera). Human sickness and death, extensive kills of aquatic animals, and other negative effects, can have elevated costs on human economy, with the recreation and tourism industry suffering the most important economic impacts, at least locally. It is concluded that levels of total nitrogen lower than 0.5-1.0 mg TN/L could prevent aquatic ecosystems (excluding those ecosystems with naturally high N levels) from developing acidification and eutrophication, at least by inorganic nitrogen pollution. Those relatively low TN levels could also protect aquatic animals against the toxicity of inorganic nitrogenous compounds since, in the absence of eutrophication, surface waters usually present relatively high concentrations of dissolved oxygen, most inorganic reactive nitrogen being in the form of nitrate. Additionally, human health and economy would be safer from the adverse effects of inorganic nitrogen pollution.

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Thomas, P., Rahman, M.S., Kummer, J.A., and Lawson, S. **Reproductive endocrine dysfunction in Atlantic croaker exposed to hypoxia.** *Marine Environmental Research* 62: S249-S252, 2006.

**Notes**: Although there is extensive evidence for impaired endocrine function in fishes exposed to environmental chemicals, information is currently lacking on reproductive endocrine effects of other environmental stressors such as hypoxia. The effects of ten weeks exposure to low dissolved oxygen (DO: 2.7 ppm and 1.7 ppm) on reproductive morphometric and endocrine responses in female Atlantic croaker (*Micropogonias undulatus*) were investigated in controlled laboratory studies, and compared to the effects observed in fish collected from hypoxic sites in Mobile Bay, Alabama. Exposure of croaker to moderate hypoxia during ovarian recrudescence, both in the laboratory and at the field sites, caused significant impairment of ovarian growth as well as decreased production of fully grown oocytes, resulting in dramatic reductions in the number of viable gametes (fecundity). Ovarian dysfunction was associated with significant decreases in endocrine indicators of the estrogen signaling pathway regulating production of vitellogenin, the yolk protein precursor sequestered by the growing oocytes. The results indicate that reproductive morphometric and endocrine biomarkers in croaker are sensitive to moderate hypoxia, and are potentially useful as early warning indicators of reproductive failure.

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Andersen, J.H., Schluter, L., and Ærtebjerg, G. **Coastal eutrophication: recent developments in definitions and implications for monitoring strategies.** *Journal of Plankton Research* 28(7): 621-628, 2006.

**Notes**: The word 'eutrophication' has its root in two Greek words: 'eu' which means 'well' and 'trope' which means 'nourishment'. The modern use of the word eutrophication is related to inputs and effects of nutrients in aquatic systems. Despite a common understanding of its causes and effects, there is no agreed definition of coastal eutrophication. This communication aims to review recent developments in the definitions of coastal eutrophication, all of which focus on 'accelerated growth', and to discuss the implications in relation to monitoring and assessment of ecological status. It is recommended that measurements of primary production, being a sensitive and accurate indicator of eutrophication, should be mandatory when monitoring and assessing the ecological status of coastal waters.

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Spokes, L., et al. **MEAD: An interdisciplinary study of the marine effects of atmospheric deposition in the Kattegat.** *Environmental Pollution* 140(3): 453-462, 2006.

**Notes**: This paper summarises the results of the EU funded MEAD project, an interdisciplinary study of the effects of atmospheric nitrogen deposition on the Kattegat Sea between Denmark and Sweden. The study considers emissions of reactive nitrogen gases, their transport, transformations, deposition and effects on algal growth together with management options to reduce these effects. We conclude that atmospheric deposition is an important source of fixed nitrogen to the region particularly in summer, when nitrogen is the limiting nutrient for phytoplankton growth, and contributes to the overall eutrophication pressures in this region. However, we also conclude that it is unlikely that atmospheric deposition can, on its own, induce algal blooms in this region. A reduction of atmospheric nitrogen loads to this region will require strategies to reduce emissions of ammonia from local agriculture and Europe wide reductions in nitrous oxide emissions.

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Barile, P.J. and Lapointe, B.E. **Atmospheric nitrogen deposition from a remote source enriches macroalgae in coral reef ecosystems near Green Turtle Cay, Abacos, Bahamas.** *Marine Pollution Bulletin* 50(11): 1262-1272, 2005.

**Notes**: Over the past several decades, the fixation of "new" nitrogen to the biosphere has doubled. For the early 21st century, the most significant rate increases in atmospheric nitrogen deposition are predicted for developing nations. Wet nitrogen deposition was assessed on the remote island of Green Turtle Cay, Bahamas in a dry and wet season from January to July 2000. Episodic deposition of nitrate (~ 1-137 mM) and ammonia (~ 2-122 mM) represented a mean deposition rate of similar to 0.2 mg DIN m(-2) yr(-1). Wet deposition of nitrogen to the climatologically-linked east coast of Florida is ~ 4 times greater than the estimated annual wet nitrogen deposition value at Green Turtle Cay, suggesting the continental US as a principal airshed for this loading source. Short-term bioassays of macroalgal productivity with a 5% rainfall solution caused depressed net productivity and increased dark respiration, well known "transient metabolic" responses by nutrient-limited tropical macroalgae. Wet deposition of inorganic nitrogen from episodic rainfall events may provide up to 20% of the "new" nitrogen necessary to meet growth demands of macroalgae on coral reefs near Green Turtle Cay.

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Jickells, T. **The role of air-sea exchange in the marine nitrogen cycle.** *Biogeosciences* 3(3): 271-280, 2006.

**Notes**: This contribution to the Spot-On volume considers the magnitude and composition of atmospheric nitrogen inputs to the oceans and then goes on to consider the impacts of these inputs. Effects in open ocean and coastal areas are probably different. Offshore atmospheric inputs may produce a small enhancement of overall ocean productivity and hence $CO_2$ drawdown. In coastal waters atmospheric inputs contribute significantly to overall eutrophication pressure, but evidence that they trigger algal blooms is limited. Management of atmospheric inputs to coastal waters to mitigate eutrophication pressures requires that emissions be managed over a wide area reflecting the efficient long range transport of atmospheric nitrogen. Strategies for management of oxidised and reduced nitrogen deposition will be different reflecting their different rates of deposition.

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Wang, B.D. **Cultural eutrophication in the Changjiang (Yangtze River) plume: History and perspective.** *Estuarine, Coastal and Shelf Science* 69(3-4): 471-477, 2006.

**Notes**: The Changjiang (Yangtze River) is known to contribute significantly to the eutrophication that has caused drastic changes to the ecosystem of the East China Sea. However, evidence for historical changes in nutrient concentrations and composition and the consequent effects on the ecosystem in the coastal water is sparse. In this paper we present some long-term data for nutrient concentrations and Si:N:P ratios in the freshwater and the river plume and the long-term response of the ecosystem structure in the river plume. These data reveal increases in the dissolved inorganic nitrogen and phosphate concentrations in the Changjiang freshwater by a factor of five from the 1960s to the end of the 1990s and a reduction in dissolved silicate by two thirds over the same period. Concomitantly, an increase in DIN concentration and a reduction in silicate concentration both by a factor of two were observed in the surface water of the Changjiang plume. As an ecological consequence to such nutrient changes, the chlorophyll *a* concentration increased by a factor of four since the 1980s and harmful algal blooms increased rapidly since 1985 in the Changjiana estuary and adjacent sea areas. The macrozoobenthic biomass decreased sharply from the mid 1980s to the present, suggesting that the Changjiang estuary has been in a high eutrophication state since that time. We predict that, due to the continuously increasing nutrient pressure, the symptoms of eutrophication associated with nutrients will worsen in the Changjiang plume in the near future.

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Destouni, G., Lindgren, G.A., and Gren, I.M. **Effects of inland nitrogen transport and attenuation modeling on coastal nitrogen load abatement.** *Environmental Science and Technology* 40(20): 6208-6214, 2006.

**Notes**: Modeling of the spatial distribution of nitrogen transport and attenuation from various inland sources and along different hydrological pathways to coastal waters is needed for relevant decisions on effective allocation of measures for coastal nitrogen load abatement. We identify, classify, and quantify uncertainties associated with main discrepancies between spatial process representations in different catchment-scale nitrogen transport-attenuation models. The results show important model differences, indicating scientific disagreement on the realistic spatial process understanding, representation, and quantification in nitrogen transport-attenuation modeling. By further developing solutions for economic optimization of spatially differentiated nitrogen source abatement in coastal catchments, we find this disagreement to considerably affect the economic efficiency of coastal nitrogen load reduction. It may also lead to stakeholder mistrust and conflict and needs to be recognized and handled in environmental policy

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Boyer, J.N., Dailey, S.K., Gibson, P.J., Rogers, M.T., and Mir-Gonzalez, D. **The role of dissolved organic matter bioavailability in promoting phytoplankton blooms in Florida Bay.** *Hydrobiologia* 569: 71-85, 2006.

**Notes**: The clear, shallow, oligotrophic waters of Florida Bay are characterized by low phytoplankton biomass, yet periodic cyanobacteria and diatom blooms do occur. We hypothesized that allochthonous dissolved organic matter (DOM) was providing a subsidy to the system in the form of bound nutrients. Water from four bay sites was incubated under natural light and dark conditions with enrichments of either DOM (> 1 kD, 2xDOM) or inorganic nutrients (N+P). Samples were analyzed for bacterial numbers, bacterial production, phytoplankton biomass, phytoplankton community structure, and production, nutrients, and alkaline phosphatase (AP) activity. The influence of 2xDOM enrichment on phytoplankton biomass developed slowly during the incubations and was relatively small compared to nutrient additions. Inorganic nutrient additions resulted in an ephemeral bloom characterized initially as cyanobacterial and brown algae but which changed to dinoflagellate and/or brown algae by day six. The DIN:TP ratio decreased 10-fold in the N+P treatments as the system progressed towards N limitation. This ratio did not change significantly for 2xDOM treatments. In addition, these experiments indicated that both autotrophic and heterotrophic microbial populations in Florida Bay may fluctuate in their limitation by organic and inorganic nutrient availability. Both N+P and 2xDOM enrichments revealed significant and positive response in bioavailability of dissolved organic carbon (BDOC). Potential BDOC ranged from 1.1 to 35.5%, with the most labile forms occurring in Whipray Basin. BDOC at all sites was stimulated by the 2xDOM addition. Except for Duck Key, BDOC at all sites was also stimulated by the addition of N+P. BDOC was lower in the dry season than in the wet season (5.56% vs. 16.86%). This may be explained by the distinct chemical characteristics of the DOM produced at different times of year. Thus, both the heterotrophic and autotrophic microbial communities in Florida Bay are modulated by bioavailability of DOM. This has ramifications for the fate of DOM from the Everglades inputs, implicating DOM bioavailability as a contributing factor in regulating the onset, persistence, and composition of phytoplankton blooms.

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Verity, P.G., Alber, M., and Bricker, S.B. **Development of hypoxia in well-mixed subtropical estuaries in the southeastern USA.** *Estuaries and Coasts* 29(4): 665-673, 2006.

**Notes**: Estuaries throughout much of the South Atlantic Bight (southeastern U.S.) have been considered to be relatively pristine, but are now experiencing elevated concentrations of both organic and inorganic nutrients. As is true in many parts of the world, this eutrophication is correlated with coastal population growth. These estuaries have been assumed to be immune from extended hypoxia, in large part because they are well mixed and do not generally exhibit the water column stratification that is traditionally associated with low concentrations of dissolved oxygen. Data presented here show long-term (19 yr) decreases in dissolved oxygen in surface waters of the Skidaway estuary, a pattern that is occurring throughout coastal Georgia. More limited data from bottom waters exhibit the same trend. The decreases in dissolved oxygen occurred at the same time as observed increases in inorganic and organic nutrients and in bacteria concentrations, implying an increase in heterotrophic activity. These observations suggest that traditional paradigms long applied to stratified estuaries, wherein the cycle that leads to hypoxia is initiated by the uptake of inorganic nutrients by autotrophs that are then decomposed below the pycnocline, may need revision for well-mixed estuaries. Heterotrophic community metabolism, stimulated by anthropogenic loading of organic and inorganic nutrients, can overwhelm even vigorous vertical mixing and horizontal exchange to gradually cause declining oxygen concentrations and eventually hypoxia.

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Martinelli, L.A., Howarth, R.W., Cuevas, E., Filoso, S., Austin, A.T., Donoso, L., Huszar, V., Keeney, D., Lara, L.L., Llerena, C., McIssac, G., Medina, E., Ortiz-Zayas, J., Scavia, D., Schindler, D.W., Soto, D., and Townsend, A. **Sources of reactive nitrogen affecting ecosystems in Latin America and the Caribbean: current trends and future perspectives.** *Biogeochemistry* 79(1-2): 3-24, 2006.

**Notes**: While the amount of reactive nitrogen circulating at the global level has increased markedly in the last century, the effects of this increase are largely seen at the regional level due to interacting ecological and socio-economic factors. In contrast with most other regions of the world, Latin America and the Caribbean (LA-Ca) stand out due to the fact that the major input of reactive nitrogen (Nr) still occurs naturally via biological nitrogen fixation (BNF) in natural ecosystems as opposed to anthropogenic inputs of synthetic fertilizer, fossil fuel combustion and cropping with leguminous species. Largely due to economic reasons, the consumption of fertilizer N in the LA-Ca region is still low in comparison with the average consumption of the world. However, the fertilizer N consumption is increasing at a much faster rate than that in developed regions of the world, like USA and Canada. The Nr production through BNF in cultivated plants that fix nitrogen (C-BNF) is 5 times lower than that occurring naturally in Latin America, but is still equivalent to 16% of the world C-BNF. The cultivation of nitrogen-fixing crop species in the LA-Ca region is also increasing, almost entirely due to the expansion of soybean fields in the central and northern regions of Brazil and the Pampa region of Argentina. Other anthropogenic activities in the region that contribute to an increase in the circulation of reactive nitrogen include the impact of biomass burning and urbanization. In the last decade, an average of 47,000 km² per year of forests was burned in the LA-Ca region. The environmental impact of urban centers in the LA-Ca region has become very important, since an intense urbanization process is occurring in this region, at an intensity that far exceeds urban development in the northern hemisphere. The consequences of increased urbanization include increased emissions of NOx to the atmosphere due to the fossil fuel combustion, and the lack of sewage treatment facilities in most cities of the LA-Ca result in a large volume of untreated sewage discharged into surface waters, creating serious environmental problems. The combination of rapid urbanization and agricultural intensification in this region suggest that concern is warranted for the potential for increase in the circulation of reactive nitrogen in the very near future. At the same time, the opportunity still exists to mitigate some of the consequences of human impact on the nitrogen cycle in a region that still maintains a large fraction of its natural ecosystems intact.

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Schindler, D.W., Dillon, P.J., and Schreier, H. **A review of anthropogenic sources of nitrogen and their effects on Canadian aquatic ecosystems.** *Biogeochemistry* 79(1-2): 25-44, 2006.

**Notes**: Nitrogen releases to air and water are low in most of Canada, but in southern areas with rapid development there are telltale signs of the problems from releases to air and water that are described elsewhere in this volume. These include higher nitrogen in water and releases to the atmosphere from urban areas, industry and agriculture. As a result, in parts of Ontario and Quebec underlain by Precambrian geology, nitrogen deposition is near the critical loads found for geologically similar

areas of Europe. In particular, combined inputs of sulphuric and nitric acids are causing base cation depletion in forest soils and keeping some lakes at pH values too low to allow the recovery of biological communities. In southern Ontario, Alberta and British Columbia, rapidly expanding human populations, industry and agriculture are causing high concentrations of nitrate in surface and groundwaters. At present, there is little sign of estuarine eutrophication in Canada, but it appears to be imminent on the Pacific coast, as the result of expanding human populations and intensifying agriculture in the lower Fraser Valley and Puget Sound. Steps should be taken now to prevent the widespread problems caused by nitrogen pollution that have occurred in Europe, the USA, and other populous and industrialized regions.

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Filoso, S., Martinelli, L.A., Howarth, R.W., Boyer, E.W., and Dentener, F. **Human activities changing the nitrogen cycle in Brazil.** *Biogeochemistry* 79(1-2): 61-89, 2006.

**Notes**: The production of reactive nitrogen worldwide has more than doubled in the last century because of human activities and population growth. Advances in our understanding of the nitrogen cycle and the impacts of anthropogenic activities on regional to global scales is largely hindered by the paucity of information about nitrogen inputs from human activities in fast-developing regions of the world such as the tropics. In this paper, we estimate nitrogen inputs and outputs in Brazil, which is the world's largest tropical country. We determined that the N cycle is increasingly controlled by human activities rather than natural processes. Nitrogen inputs to Brazil from human activities practically doubled from 1995 to 2002, mostly because of nitrogen production through biological fixation in agricultural systems. This is in contrast to industrialized countries of the temperate zone, where fertilizer application and atmospheric deposition are the main sources of anthropogenic nitrogen. In Brazil, the production of soybean crops over an area of less than 20 million ha, was responsible for about 3.2 Tg N or close to one-third of the N inputs from anthropogenic sources in 2002. Moreover, cattle pastures account for almost 70% of the estimated 280 x 10(6) ha of agricultural land in Brazil and potentially fix significant amounts of N when well managed, further increasing the importance of biological nitrogen fixation in the nitrogen budget. Much of these anthropogenic inputs occur in the Brazilian savannah region (Cerrado), while more urbanized regions such as the state of Sao Paulo also have high rates of nitrogenous fertilizer inputs. In the Amazon, rates of anthropogenic nitrogen inputs are relatively low, but continuing conversion of natural forests into cattle pasture or secondary forests potentially add a significant amount of new nitrogen to Brazil given the vast area of the region. Better measurements of biological fixation rates in Brazil are necessary for improving the nitrogen budgets, especially at a more refined spatial scale.

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Howarth, R.W., Swaney, D.P., Boyer, E.W., Marino, R., Jaworski, N., and Goodale, C. **The influence of climate on average nitrogen export from large watersheds in the Northeastern United States.** *Biogeochemistry* 79(1-2): 163-186, 2006.

**Notes**: The flux of nitrogen in large rivers in North America and Europe is well explained as a function of the net anthropogenic inputs of nitrogen to the landscape, with on average 20 to 25% of these inputs exported in rivers and 75 to 80% of the nitrogen retained or denitrified in the landscape. Here, we use data for average riverine nitrogen fluxes and anthropogenic inputs of nitrogen over a 6-year period (1988-1993) for 16 major watersheds in the northeastern United States to examine if there is also a climatic influence on nitrogen fluxes in rivers. Previous studies have shown that for any given river, nitrogen fluxes are greater in years with higher discharge, but this can be interpreted as storage of nitrogen in the landscape during dry years and flushing of this stored nitrogen during wet years. Our analyses demonstrate that there is also a longer-term steady-state influence of climate on riverine nitrogen fluxes. Those watersheds that have higher precipitation and higher discharge export a greater fraction of the net anthropogenic inputs of nitrogen. This fractional export ranges from 10 to 15% of the nitrogen inputs in drier watersheds in the northeastern United States to over 35% in the wetter watersheds. We believe this is driven by lower rates of denitrification in the wetter watersheds, perhaps because shorter water residence times do not allow for as much denitrification in riparian wetlands and low-order streams. Using mean projections for the consequences of future climate change on precipitation and discharge, we estimate that nitrogen fluxes in the Susquehanna River to Chesapeake Bay may increase by 3 to 17% by 2030 and by 16 to 65% by 2095 due to greater fractional delivery of net anthropogenic nitrogen inputs as precipitation and discharge increase. Although these projections are highly uncertain, they suggest a need to better consider the influence of climate on riverine nitrogen fluxes as part of management efforts to control coastal nitrogen pollution.

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Scavia, D. and Bricker, S.B. **Coastal eutrophication assessment in the United States.** *Biogeochemistry* 79(1-2): 187-208, 2006.

**Notes**: Recent national assessments document that nitrogen-driven coastal eutrophication is widespread and increasing in the United States. This significant coastal pollution problem includes impacts including increased areas and severity of hypoxic and anoxic waters; alteration of food webs; degradation and loss of sea grass beds, kelp beds and coral reefs; loss of biodiversity; and increased incidences and duration of harmful algal blooms. In this paper, we review two complementary approaches to assessing the causes and consequences of these trends, as well as potential remedies for them. The first is a national-scale assessment, drawn primarily from expert knowledge of those most familiar with the individual estuaries and integrated into a common analysis framework. The second approach, focused on the Mississippi/ Atchafalaya basin - the largest US drainage basin - draws upon both quantitative and qualitative analyses within a comprehensive framework, Integrated Assessment.

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Smith, V.H. **Responses of estuarine and coastal marine phytoplankton to nitrogen and phosphorus enrichment.** *Limnology and Oceanography* 51(1): 377-384, 2006.

**Notes**: A cross-ecosystem comparison of data obtained from 92 coastal zone ecosystems worldwide revealed a strong positive response of marine phytoplankton biomass to nutrient enrichment that is highly consistent with the general patterns reported previously in the limnological literature for freshwater lakes and reservoirs. Average concentrations of chlorophyll *a* in estuarine and coastal marine systems were strongly dependent on the mean concentrations of total nitrogen and total phosphorus in the water column. Moreover, as is true of freshwater ecosystems, the identity of the primary growth-limiting nutrient for marine phytoplankton appeared to be generally predictable from water-column total nitrogen:total phosphorus (TN:TP) ratios. This similarity in physiological response to nutrients likely derives from the shared evolutionary histories of marine and freshwater phytoplankton.

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Clarke, A.L., Weckstrom, K., Conley, D.J., Anderson, N.J., Adser, F., Andren, E., deJonge, V.N., Ellegaard, M., Juggins, S., Kauppila, P., Korhola, A., Reuss, N., Telford, R. J., and Vaalgamaa, S. **Long-term trends in eutrophication and nutrients in the coastal zone.** *Limnology and Oceanography* 51(1): 385-397, 2006.

**Notes**: We used high-resolution paleoecological records of environmental change to study the rate and magnitude of eutrophication over the last century in two contrasting coastal ecosystems. A multiproxy approach using geochemical and biological indicators and diatom-based transfer functions provides a long-term perspective on changes in nutrient concentrations and the corresponding biological and sedimentary responses. In Roskilde Fjord, Denmark, total nitrogen (TN) increased 85% during the last century, with the most rapid increase occurring after the 1950s, corresponding to the postwar increase in N fertilizer use. In LaaJalahti Bay, an urban embayment near Helsinki, Finland, total dissolved nitrogen (TDN) increased with growing wastewater inputs and decreased with the remedial actions taken to reduce these discharges. These changes are small relative to the order of magnitude increases in nutrient loading that have occurred in northwestern Europe, where the dissolved inorganic nitrogen (DIN) load has increased more than threefold in certain areas.

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Carstensen, J., Conley, D.J., Andersen, J.H., and Ærtebjerg, G. **Coastal eutrophication and trend reversal: A Danish case study.** *Limnology and Oceanography* 51(1): 398-408, 2006.

**Notes**: In the past 2 decades significant measures have been taken to reduce nitrogen and phosphorus discharges from Denmark by 50% and 80%, respectively. These nutrient reduction targets now appear within reach after several consecutive reduction measures are fully implemented, particularly toward diffuse discharges, and reduced nutrient concentrations are beginning to be observed in estuaries and the Danish straits. Phosphorus concentrations have declined by 22% to 57% from the early 1990s, mainly owing to improved treatment of urban and industrial wastewater. Changes in nitrogen concentrations, following reduction measures toward diffuse sources, were more recent and partly masked by large interannual variations in freshwater discharge. The response in marine nitrogen concentrations was delayed relative to the decline in riverine concentrations, most likely owing to large internal loading from the sediments. Two consecutive dry years appeared to be the triggering mechanism for nitrogen concentrations to decline. In the last 5 yr, nitrogen levels in estuaries and coastal waters

have decreased up to 44% when interannual variations in freshwater discharge were accounted for. These first signs of environmental recovery were most pronounced in estuaries and coastal waters but also were apparent in open waters of the Kattegat, the Sound, and the Belt Sea. This case study is the first to document significant decreases in nutrient concentrations on a large regional scale resulting from an active management strategy to reduce nutrients from both diffuse and point sources.

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Paerl, H.W., Valdes, L.M., Peierls, B.L., Adolf, J.E., and Harding, L.W. **Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems.** *Limnology and Oceanography* 51(1): 448-462, 2006.

**Notes**: We examined the effects of anthropogenic and climatic perturbations on nutrient-phytoplankton interactions and eutrophication in the waters of the largest estuarine systems in the U.S.A., the Chesapeake Bay (CB), Maryland/Virginia, and the Neuse River Estuary/Pamlico Sound (NRE/PS) system, North Carolina. Both systems have experienced large post-World War II increases in nitrogen (N) and phosphorus (P) loading, and nutrient reductions have been initiated to alleviate symptoms of eutrophication. However, ecosystem-level effects of these nutrient reductions are strongly affected by hydrologic variability, including severe droughts and a recent increase in Atlantic hurricane activity. Phytoplankton community responses to these hydrologic perturbations, including storm surges and floods, were examined and when possible, compared for these systems. In both systems, the resulting variability in water residence time strongly influenced seasonal and longer-term patterns of phytoplankton biomass and community composition. Fast-growing diatoms were favored during years of high discharge and short residence time in CB, whereas this effect was not observed during high discharge conditions in the longer residence time NRE/PS. In the NRE/PS, all phytoplankton groups except summer cyanobacterial populations showed decreased abundance during elevated flow years when compared to low flow years. Although hurricanes affected the CB less frequently than the NRE/PS, they nonetheless influenced floral composition in both systems. Seasonally, hydrologic perturbations, including droughts, floods, and storm-related deep mixing events, overwhelmed nutrient controls on floral composition. This underscores the difficulty in predicting seasonal and longer-term phytoplankton production and compositional responses to nutrient input reductions aimed at controlling eutrophication of large estuarine ecosystems.

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Parsons, M.L., Dortch, Q., Turner, R.E., and Rabalais, N.R. **Reconstructing the development of eutrophication in Louisiana salt marshes.** *Limnology and Oceanography* 51(1): 534-544, 2006.

**Notes**: We collected sediment cores from three salt marsh ponds in coastal Louisiana to test the usefulness of proxies of eutrophication. One-centimeter increments of Pb-210- and Cs-137-dated sediment were analyzed for diatoms, pigments (phaeophytin and chlorophyll *a*), biogenic silica, percentage organic matter, percentage carbon, and percentage nitrogen. Both sediment chlorophyll *a* and a diatom-based trophic index (TI) were significantly and positively correlated with riverine or local nutrient indices. Two diatom species, *Amphora copulata* Giffen and *Navicula yarrensis* Grunow, were significantly and negatively correlated with riverine and local nutrient indices. These results suggest that these variables can be used as potential indicators of trophic status. Results from a complete-linkage cluster analysis on the diatom assemblage data demonstrated that the sediment cores could be split into three time periods: early 1900s (pre-1930s/1940s), mid-1900s (1930s/40s to 1960s/1970s), and late 1900s (1960s/70s to 1990s). Examination of the sediment chlorophyll *a* and TI data over these time periods, coupled with an analysis of variance of nutrient inputs between the time periods, suggests that nutrient loading increased dramatically from the mid-1960s to the mid-1970s. This study demonstrates that (1) a retrospective analysis of sediment cores can be conducted in highly variable salt marsh ponds and (2) these salt marsh environments are already affected by the higher nutrient loads from both riverine and local processes occurring over the last 50 years. Additional nutrient loading, e.g., from river diversion projects for the lower Mississippi River, may exacerbate eutrophication already evident in the marsh environment.

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Worm, B. and Lotze, H.K. **Effects of eutrophication, grazing, and algal blooms on rocky shores.** *Limnology and Oceanography* 51(1): 569-579, 2006.

**Notes**: Eutrophication can profoundly change rocky shore communities. These changes often cause the replacement of perennial, canopy-forming algae such as *Fucus* spp. with annual, bloom-forming algae such as *Enteromorpha* spp. Grazing, however, can counteract eutrophication by eliminating the annual algae's susceptible recruits. We examine these generalizations across large scales. We use replicated "bioassay" experiments to compare the effects of eutrophication and grazing across four paired control versus eutrophied sites in the Northwest Atlantic and four eutrophied sites in the Baltic Sea

in spring and summer. At each site, annual algal recruitment and grazing pressure were estimated using tiles seeded with *Enteromorpha intestinalis* propagules. Tiles were exposed for 3 weeks with grazers excluded or allowed access. Productivity of *E. intestinalis* recruits was strongly related to eutrophication (10-fold increase) and grazing (80% decrease) and was weakly related to season. While the absolute grazing rate increased in a linear fashion with algal productivity, the relative grazing rate remained surprisingly constant (~ 80%). Comparative field surveys showed that perennial algae decreased by 30-60%, while annual algae, filter feeders, and grazers increased across a gradient of eutrophication. As eutrophication increased from control to eutrophied to point source sites, rocky shore communities became increasingly dominated by single species of annual algae or filter feeders, and community diversity declined consistently by 24-46%. We conclude that grazers are important controllers of algal blooms but that, ultimately, they cannot override the effects of increasing eutrophication on rocky shore community structure and biodiversity.

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Howarth, R.W. and Marino, R. **Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades.** *Limnology and Oceanography* 51(1): 364-376, 2006.

**Notes**: The first special volume of Limnology and Oceanography, published in 1972, focused on whether phosphorus (P) or carbon (C) is the major agent causing eutrophication in aquatic ecosystems. Only slight mention was made that estuaries may behave differently from lakes and that nitrogen (N) may cause eutrophication in estuaries. In the following decade, an understanding of eutrophication in estuaries proceeded in relative isolation from the community of scientists studying lakes. National water quality policy in the United States was directed almost solely toward P control for both lakes and estuaries, and similarly, European nations tended to focus on P control in lakes. Although bioassay data indicated N control of eutrophication in estuaries as early as the 1970s, this body of knowledge was treated with skepticism by many freshwater scientists and water-quality managers, because bioassay data in lakes often did not properly indicate the importance of P relative to C in those ecosystems. Hence, the bioassay data in estuaries had little influence on water-quality management. Over the past two decades, a strong consensus has evolved among the scientific community that N is the primary cause of eutrophication in many coastal ecosystems. The development of this consensus was based in part on data from whole-ecosystem studies and on a growing body of evidence that presented convincing mechanistic reasons why the controls of eutrophication in lakes and coastal marine ecosystems may differ. Even though N is probably the major cause of eutrophication in most coastal systems in the temperate zone, optimal management of coastal eutrophication suggests controlling both N and P, in part because P can limit primary production in some systems. In addition, excess P in estuaries can interact with the availability of N and silica (Si) to adversely affect ecological structure. Reduction of P to upstream freshwater ecosystems can also benefit coastal marine ecosystems through mechanisms such as increased Si fluxes.

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Burkholder, J.M., Dickey, D.A., Kinder, C.A., Reed, R.E., Mallin, M.A., McIver, M.R., Cahoon, L.B., Melia, G., Brownie, C., Smith, J., Deamer, N., Springer, J., Glasgow, H.B., and Toms, D. **Comprehensive trend analysis of nutrients and related variables in a large eutrophic estuary: A decadal study of anthropogenic and climatic influences.** *Limnology and Oceanography* 51(1): 463-487, 2006.

**Notes**: We used a decadal data set, with weekly to biweekly sampling in April-October and monthly sampling in November-March, to characterize climatic (hurricane-level storms, a sustained 3-yr drought) and anthropogenic influences on N and P concentrations and loadings to a large eutrophic, poorly flushed estuary, the Neuse Estuary of the Albemarle-Pamlico Estuarine System. Mass volume transport data were obtained with cross-estuary transect flow measurements taken near the entrance to the estuary. Although trends were minimally influenced by hurricanes, analyses were significantly affected by the sustained drought near the end of the study. As examples, decreasing trends in total N (TN), total P (TP), and bottom-water dissolved oxygen concentrations, and in TN loadings were significant considering all data, but these trends were not significant when the sustained drought was excluded from analysis. In addition, the trend in TN loading was especially sensitive to the initial sampling period. $NH_4^+$ concentrations dramatically increased (overall by ~ 500%) as a persistent trend regardless of attempts to control for climatic events. An increasing trend in $NH_4^+$ also was documented in an adjacent, rapidly flushed Coastal Plain estuary, the Cape Fear. The $NH_4^+$ data suggest a regional-scale effect of high inputs from inadequately controlled, increasing nonpoint sources. The fragility of TN loading trends, the striking increase in $NH_4^+$ concentrations, and the lack of management emphasis on controlling nonpoint sources such as "new" industrialized swine production collectively do not support recent reports of achievement of a 30% reduction in TN loading to the Neuse. Nonpoint sources remain a critical target for reduction to alleviate the negative effects of cultural eutrophication in this system, as in many estuaries throughout the world.