Controlling Eutrophication: Nitrogen and Phosphorus

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Controlling Eutrophication: Nitrogen and Phosphorus

Improvements in the water quality of many freshwater and most coastal marine ecosystems requires reductions in both nitrogen and phosphorus inputs.

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The need to reduce anthropogenic nutrient inputs to aquatic ecosystems in order to protect drinking-water supplies and to reduce eutrophication, including the proliferation of harmful algal blooms (*1*) and "dead zones" in coastal marine ecosystems (*2*) has been widely recognized. However, the costs of doing this are substantial; hence, developing the appropriate nutrient management strategy is very important. Nitrogen (N), needed for protein synthesis, and phosphorus (P), needed for DNA, RNA, and energy transfer, are both required to support aquatic plant growth and are the key limiting nutrients in most aquatic and terrestrial ecosystems. However, a cascading set of consequences has been set in motion, arising from massive increases in fixed N additions to the biosphere, largely through the production of fertilizers and increases in fossil fuel emissions (*3*). P levels have also significantly increased because of fertilizer use, as well as from municipal and industrial wastewater. Here, we explore the rationale for dual–nutrient reduction strategies for aquatic ecosystems, especially in estuarine and coastal marine regions.

The question of whether one or both nutrients should be controlled to reverse the detrimental effects of eutrophication of lakes was thought to be solved in the early 1970s by Schindler (*4*), who established that P was the primary limiting nutrient in remarkable long-term experimental manipulations at Lake 227 in the Experimental Lakes Area, Canada (*5*). These and other results (*6*) led to widespread reductions in P loading to North American and European lakes and consequent improvements in water quality (*7*). On the basis of lake examples, P controls were prescribed by environmental regulatory agencies for estuarine and coastal marine ecosystems as well (*8*). P-reduction programs improved water quality in many lakes, but broader water- and environmental-quality goals were not achieved, particularly in estuaries and coastal marine ecosystems. This led to the general recognition of the need to control N input to coastal waters (*9*).

Too much algae. **(Top)** Removing macroalgal blooms at the Olympic Sailing venue, China. **(Middle)** Seagrasses covered with attached algae in a Danish estuary. **(Bottom)** Non–N2-fixing cyanobacteria blooms in Lake Okeechobee, Florida, U.S.A.

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In lakes, the key symptom of eutrophication is cyanobacterial blooms (see figure, left). Planktonic N_2-fixing cyanobacteria bloom in fresh waters when P is replete and N availability is low. Such blooms are undesirable because cyanobacteria can be toxic, cause hypoxia, and disrupt food webs (*1*, *10*). N_2 fixation by cyanobacteria also can help to alleviate N shortages and hence maintain a lake in a P-limited condition (*5*).

N_2 fixation by planktonic cyanobacteria is much less likely in estuaries and coastal seas than in lakes. Significant coastal planktonic N_2 fixation has not been observed at salinities greater than 8 to 10 (ocean salinity is ~35), even in estuaries that are strongly N-limited, except in rare cases (*11*). If N limitation were the only factor governing blooms of N_2-fixing cyanobacteria, then their blooms would be widespread in estuarine and coastal marine ecosystems around the world, and they are not. Thus, reducing N loads to the saline waters of estuaries should not cause blooms of N_2-fixing cyanobacteria (*5*). Furthermore, estuarine and coastal marine ecosystem eutrophication results in loss of seagrasses and hypoxia (*2*), which are more serious recurrent problems than cyanobacterial blooms (see the figure).

Why is N_2 fixation in the saline waters of estuaries and coastal marine ecosystems so much less than that in lakes, and why is this process unresponsive to reduced N loads in estuaries? Numerous hypotheses have been put forward (*10*, *12*). Most researchers have concluded that no single factor is responsible, but rather interactions between two or more factors control the rates (*13*, *14*). Mesocosm experiments in Narragansett Bay (*12*) have indicated that the combination of slow growth rate from sulfate inhibition of molybdenum uptake and zooplankton grazing limited the accumulation of N_2-fixing cyanobacteria. Globally, significant N_2 fixation, particularly by the cyanobacterium *Trichodesmium*, does occur in the tropical and subtropical ocean,

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where denitrification depletes the available N and can be limited by P and Fe (*15*), but is not found in the more productive waters of estuaries and coastal seas.

P-only reduction strategies are likely to fail in Lakes Apopka, George, and Okeechobee, USA; Lakes Taihu and Donghu in China; and Lake Kasumigaura in Japan (*16*). In these lakes, P is rapidly recycled between sediments and water, and phytoplankton is dominated by non–N_2-fixing cyanobacteria, such as *Planktolyngbya*, *Oscillatoria*, and toxic *Microcystis*. *Microcystis* can vertically migrate, consume excess phosphorus at the sediment-water interface, and then rise to the water surface to form blooms (*10*). Careful simultaneous control of both P and N is required in such lakes to effectively control *Microcystis* and N_2 fixers.

Estuaries and coastal marine ecosystems that have been heavily loaded with nutrients can display P limitation, N limitation, and colimitation (*17*), and what nutrient is most limiting can change both seasonally and spatially (*18*). At the transition between fresh and saline water, P can often be the limiting nutrient (*17*, *19*). P and dissolved silicate are also often limiting during the spring, with N limitation commonly occurring during summer months (*18*). Algal production during summer is supported by rapidly recycled P within the water column or released from sediments. This condition is particularly true for coastal ecosystems, where the elevated salinity provides sulfate for microbial reduction in bottom sediments, which results in the release of large quantities of P (*19*). Also, although much of the P in freshwater systems is not biologically available because it is adsorbed by clay and other particles, a considerable fraction of the P desorbs as readily available, dissolved phosphate under saline conditions (*13*). Thus, as the summer progresses, available P increases as N declines and is not effectively compensated by N_2 fixation.

Pristine lakes are sufficiently different from estuarine and coastal marine ecosystems that they may be poor analogs (*5*). For example, the low-salinity conditions of the Baltic Sea present a complex situation where N_2 fixation does play an important role. The Baltic exhibits permanent bottom-water hypoxia (*20*), which increases N loss due to denitrification and anaerobic ammonium oxidation (annamox) at the interface between oxygenated and deoxygenated waters. The hypoxic conditions also result in injection of large amounts of P back into surface waters during deep winter mixing (*21*). The annual variation in sediment releases of P due to hypoxia is nearly an order of magnitude greater than the controllable P loads (*20*). Nitrogen has clearly been established as the nutrient limiting spring phytoplankton production; it is the sinking spring bloom that sends organic matter to bottom waters, which partly sustains hypoxia. The excess P in the water column leads to summer blooms of cyanobacteria, some of which are N_2 fixers that increase N concentrations in surface waters when they are abundant. This new N helps to sustain the springtime production and produces a "vicious circle" of eutrophication (*21*). Models suggest that, here, too, reductions in the inputs of both P and N are required for significant improvements in dissolved oxygen concentrations, transparency, and other water-quality conditions in the Baltic Sea (*22*).

Controlling only P inputs to freshwaters and ignoring the large anthropogenic inputs of N can reduce algal uptake of N and thus allow more N to be transported downstream where it can exacerbate eutrophication problems in estuarine and coastal marine ecosystems (*13*). For example, reductions in P loadings by improved wastewater treatment and banning the use of P-based detergents succeeded in arresting algal blooms in freshwater portions of the Neuse River estuary, North Carolina, USA, but increased eutrophication and hypoxia downstream in the estuary, where P is more rapidly recycled (*11*). Similarly, dramatic reductions in P loading from the Rhine River and other rivers draining into the North Sea before concomitant N reductions resulted in strong P limitation in the river plume, but greater N export, exacerbating eutrophication in waters of the Wadden Sea (*23*) and as far away as the Norwegian coast of the Skagerrak (*24*). Reductions in P loading have also been suggested to limit phytoplankton growth in the plume of the Mississippi River in the northern Gulf of Mexico, which was previously more strongly limited by N. However, the increasing and excessive loading of N, relative to P, from agriculture has driven the plume of the Mississippi River to periodic P limitation, especially during the spring bloom period (*25*). Implementing only P reductions without reducing N loads could displace the dead zone westward and increase its size (*26*).

It is prudent, and in most cases essential, to implement a dual–nutrient-reduction strategy when developing measures to control eutrophication. A focus on only P or N reduction should not be considered unless there is clear evidence or strong reasoning that a focus on only one nutrient is justified in that ecosystem and will not harm downstream ecosystems. Just as care should be taken to avoid reducing N inputs in a way that will increase compensating N_2 fixation, attention should also be given to avoid displacing the effects of eutrophication downstream by concentrating only on P in freshwater systems and avoiding watershed N reductions that can be very important for coastal marine ecosystems. Although some would suggest that management strategies that control one nutrient, such as the reduced use of fertilizers, handling of manure, soil conservation practices, and restoring wetlands and riparian buffers, would also control the other, this is not always the case (*27*). For example, the technologies for wastewater treatment to reduce P versus N differ markedly, and reducing atmospheric N deposition does not affect P inputs to aquatic ecosystems. Alleviation of eutrophication in aquatic ecosystems along the land-ocean continuum requires a balanced and strategic approach to control both nutrients appropriately.

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