River Conservation
Challenges and Opportunities

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Chapter 4 Offprint

Nutrient Pollution: A Problem with Solutions

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CHAPTER 4

Nutrient Pollution: A Problem with Solutions

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Nutrient pollution of rivers is one of the most widespread human impacts on water resources. Wastewaters from urban and agricultural activities are the source of most nutrients, which stimulate excessive growths of algae. Algal blooms can physically alter the structure of habitats, increase productivity of food webs, decrease oxygen concentration, and increase pH of waters, which causes complex effects on the productivity and biodiversity of algae, invertebrates, and fish. At low and intermediate levels of nutrient pollution, productivity of invertebrates and fish can increase with nutrient pollution, but high levels of nutrient pollution cause low oxygen that reduces animal productivity. Whereas the number of all species of algae, invertebrates, and fish may not be reduced greatly by low and intermediate levels, the numbers of sensitive species are reduced. In addition to nutrient effects on biodiversity, nutrient pollution reduces the drinking water, recreational, and fisheries uses of rivers as well as the downstream receiving waters. Algae growing in high nutrient conditions commonly produce toxins that affect drinking water as well as aquatic biodiversity. Reductions in water transparency from algae and excessive growth of algae and aquatic plants on river bottoms can reduce value of rivers for boating, swimming, and fishing. Nutrients in rivers are transported to downstream lakes and coastal zones, where problems with hypoxia and harmful algal blooms are increasing around the world. Now is the time for developing comprehensive nutrient management strategies for rivers and downstream waters. Scientific evidence clearly shows that nutrients in rivers cause important problems that severely affect ecosystem services and human well being. Threshold responses by rivers to nutrient pollution help develop stakeholder consensus for management goals. Freshwater science is sufficient for developing site-specific management goals accounting for differences in uses of rivers, in river responses to nutrient pollution, and for regional needs. Cost effective strategies exist for reducing nutrient pollution. Scientists, policy makers, and other stakeholders should seize the opportunity to advance nutrient management in rivers and thereby improve and protect the ecosystems services provided by rivers and downstream waters.

4.1. Nutrients: Necessary but spelling of harmful when in excess

Nutrients are chemicals needed by organisms to survive, grow, and reproduce. Autotrophs are organisms needing only inorganic nutrients, such as water, carbon dioxide, nitrate, and phosphate, plus the energy from sunlight and photosynthesis to make the organic molecules that compose cell parts and enable growth and reproduction. Algae and aquatic plants are autotrophs in rivers. In contrast to autotrophs, heterotrophs need organic molecules for energy and for nutrition. Fungi and most bacteria, other than cyanobacteria, are heterotrophs that require organic molecules as a source of energy and a wide diversity of inorganic and organic chemicals for nutrition. The combination of chemicals needed by these microbes depends upon the species. Animals require organic molecules as a source of energy and nutrition. Thus, the basic supply of inorganic nutrients and sunlight regulate how rapidly organisms grow in an ecosystem, and often the biomass of organisms that occur. In river ecology and management, nutrients usually refer to the inorganic chemicals needed by autotrophs.

Inorganic nutrients occur naturally in ecosystems, originating from dissolution of rocks, the bacterial process of nitrogen fixation in which atmospheric nitrogen (N_2) is converted to ammonia (NH_3), and from decomposition of dead organisms by bacteria and fungi. Nutrients are transported to rivers via runoff and subsurface groundwater flows. Because types of rocks, terrestrial vegetation sequestering nutrients, and precipitation vary from one region to another, naturally occurring nutrient concentrations vary among rivers in regions with different geology and climate (Smith et al. 2003). Nutrient generating processes are usually relatively low compared to demand in ecosystems, so most ecosystems without nutrient pollution by humans have very low nutrient concentrations. The macronutrients nitrogen and phosphorus are important among all the nutrients in aquatic ecosystems, because they are usually in shortest supply compared to the others. When they are in short supply, they limit the rate that algae and plants can grow. Phosphate, nitrate, and ammonia are the forms of phosphorus and nitrogen used by algae and plants. In general, terrestrial and marine ecosystems tend to be more limited by nitrogen than phosphorus, and freshwater ecosystems tend to be more limited by phosphorus than nitrogen.

The sources of nutrients and impacts of nutrients on rivers and downstream waters are widespread (Carpenter et al. 1998; Smith 2003; Foley et al. 2005). Even in the US, with relatively low impacts to river catchments, almost half of the length of streams and rivers have been altered by nutrients. Nutrient alterations of ecosystems tend to be greatest in climatic and geological regions in which humans can develop cities and grow food, what Ellis and Ramankutty (2008) have called "anthropogenic biomes". Most nutrient pollution originates from excess fertilization of terrestrial habitats (particularly croplands) and the waste of human and animal symbionts (chickens, cattle, pigs, etc.).

Nutrient pollution of rivers also affects lakes and coastal zones. Nutrient pollution causes widespread problems with loss of biodiversity, drinking water, and recreational uses of water

Nutrient pollution causes excessive growth of algae and plants, which leads to other imbalances in aquatic ecosystems. Excess algae and plant growth in aquatic habitats can: 1) physically alter habitats by overgrowing rocks, sands, and bottom sediments and 2) chemically alter habitats by reducing dissolved oxygen, increasing pH, and even producing toxins. Most aquatic species cannot tolerate low dissolved oxygen, high pH, and physically congested habitats. In addition, many naturally occurring species are adapted to living in low nutrient habitats. High nutrient concentrations allow invasion of species that require the higher levels of nutrients and productivity to survive, which can cause shifts in competitive balances and loss of species adapted to low nutrients and productivity. In addition to problems with nutrients altering biodiversity, the algae growing in high nutrient environments can produce toxins and precursors for toxins that foul drinking water, potentially increase persistence of pathogenic bacteria, and reduce aesthetic appeal of rivers as algae overgrow substrata and cloud the water. In both developed and undeveloped regions of the world, including many areas of Europe and the US, groundwater is contaminated with sufficiently high concentrations of nitrate that it is dangerous for human consumption (Townsend et al. 2003). "Blue-baby" syndrome (methemoglobinemia) and a diversity of cancers have been associated with high nitrate in drinking water.

Nutrient alteration of rivers also causes downstream impacts on lakes, estuaries, and coastal zones. Lewis (2011) estimates a 74 percent increase in algal and aquatic plant production in lakes since 1970. Seitzinger et al. (2010) estimated nutrient exports from rivers to coastal zones have increased 15 percent since 1970. The result has been extensive development of harmful algal blooms and low oxygen conditions in coastal zones around the world (Rabalais et al. 2010). Climate change as a result of global warming is expected to increase intensity of rainfall and flooding, which will increase nutrient transport from land and rivers to downstream waters. In addition, use of fertilizers and intensity of agriculture is expected to increase in the next 50 years as demand for food increases by a growing world population. So need for nutrient management in rivers is critical for both instream and downstream conditions.

The problems with managing nutrient pollution are somewhat different than other contaminants of rivers and other aquatic habitats. As with other

Box 4.1

Algae everywhere

Algae and aquatic plants are a highly diverse group of photosynthetic organisms that live in all aquatic habitats. Algae are distinguished from plants because they do not have sterile cells around reproductive structures. Since algal reproductive structures are sensitive to dry conditions, algae are restricted to life in water. Cyanobacteria were the first organisms that evolved the photosynthetic processes that produce oxygen, resulting in increased oxygen in the atmosphere of the earth over 2.5 billion years ago. Cyanobacteria, green algae, and diatoms are the three most common algae in most freshwater ecosystems. Green algae are green because they have a dominance of chlorophyll pigments in chloroplasts,

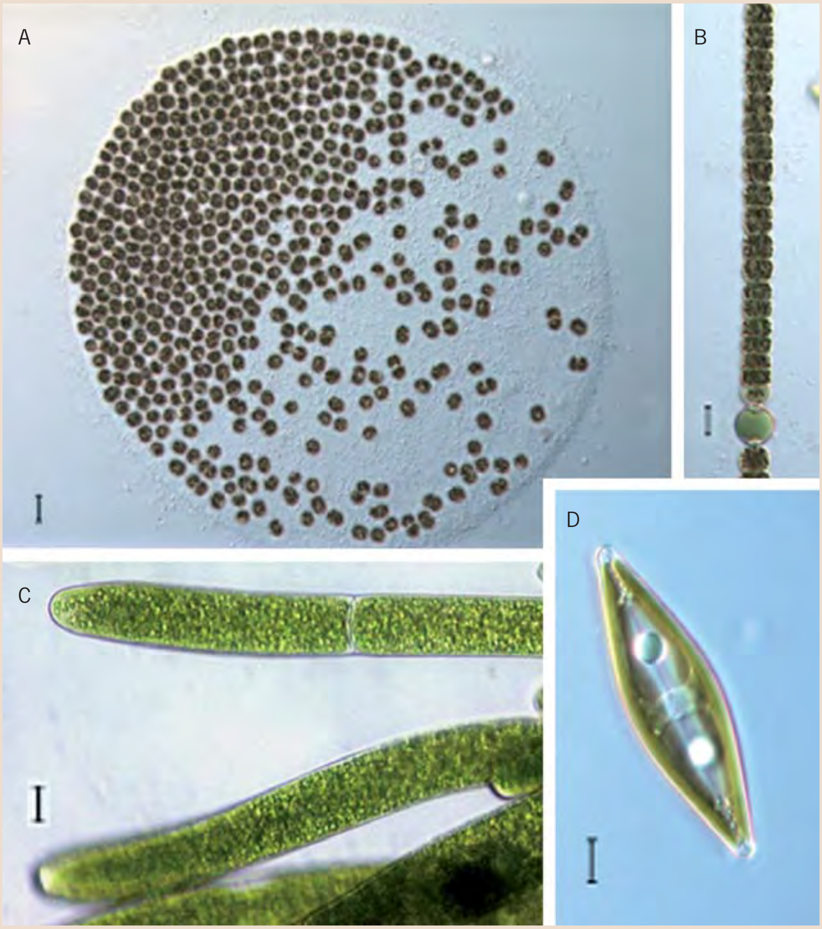


Figure 4.1: *A)* Microcystis, *a colonial cyanobacterium, which is known to produce toxins. B)* Anabaena, *a filamentous cyanobacterium with a heterocyst to fix nitrogen. C)* Cladophora, *a green algae. D)* Craticula, *a diatom. The scale bars in A-D indicate 10 μm*

which reflect green light. Although all three groups have green chlorophyll pigments, accessory pigments cause cyanobacteria to be blue-green and diatoms to be golden-brown. Cyanobacteria are unusual because they can fix atmospheric nitrogen into ammonia. Green algae have thick cellulose walls around each cell and store starch from excess photosynthesis. Diatoms have glass cell walls and store oil from excess photosynthesis. The glass cell wall is composed of two halves that separate during cell reproduction. Because of the glass cell wall, diatom growth can be limited by silica availability, as well as phosphorus and nitrogen availability. Aquatic plants range taxonomically from the primitive mosses that are common in headwater streams to the flowering plants. Some aquatic plants are adapted for fast current with long narrow leaves, whereas others may have floating leaves and live in margins of wetland streams and rivers.

contaminants, we are concerned about instream and downstream effects and the concentrations of contaminants that have negative effects on valued ecological attributes. Nutrients do not usually have direct toxic effects on organisms, so perceived risks by the public for nutrient contamination are not as great as contaminating valuable resources with toxic substances, like mercury and PCBs. However, scientific evidence is clear that high levels of nutrient pollution impair drinking water quality, public health, recreational uses of water, and biodiversity (Townsend et al. 2003; Downing et al. 2001; Suplee et al. 2008). Intermediate levels of nutrient pollution are not known to have great effects on drinking water quality and human health, but they can impair biodiversity. For some uses of rivers as well as the surrounding catchment, intermediate levels of nutrient pollution resulting from exploiting services of agricultural ecosystems can actually have positive effects on some ecosystem processes and some measures of biodiversity when high nutrient taxa invade. Effects of nutrients vary depending upon climatic and geological setting. Thus tradeoffs in managing rivers for one use or another and natural variability among regions present challenges for resource managers determining goals for resource management and pollution allowances that protect those goals.

In the following sections, we discuss effects of nutrients on biodiversity and human uses of rivers. We explore the effects of nutrients on algae, invertebrates, and fish as well as sources of nutrients. The challenges of measuring biodiversity and characterizing effects of nutrients on biodiversity are discussed. Finally, we discuss the possible solutions for land and waste management that can minimize nutrient pollution as well as strategies for reducing tradeoffs in managing rivers for their many uses.

4.2. Nutrient effects on algae

Nutrients enable growth of algae, plants, and bacteria in streams. Nutrient uptake rates, growth, and biomass accumulation rates increase asymptotically with increasing nutrient concentrations (Figure 4.2). Uptake occurs by active transport of nutrient ions through uptake sites in cell membranes, so uptake increases with nutrient concentration until all uptake sites are active. Nutrient uptake rates can exceed diffusion rates of nutrients to cells. In addition, as algae accumulate on substrata, flow of stream water through microscopic spaces among the algae slows. As a result, nutrient uptake and cell growth rates decrease with increasing algal density (Figure 4.2).

Algae-nutrient relationships become more complicated when put in the context of the complexity of river ecosystems. First, algae-nutrient relationships vary depending upon where algae are in the river. We should distinguish between benthic algae that are attached to the bottom of rivers and planktonic algae that are suspended in the water. Benthic and planktonic algae grow independently in their respective habitats, but they also interact as planktonic algae settle onto the bottom of rivers and grow and benthic algae drift from the river bottom and become suspended in the water column. With more light reaching the bottom of shallow streams, headwater and mid-sized rivers often have more benthic than planktonic algae. As waters flow slowly downstream planktonic algae grow and accumulate in the water column, reducing light penetration to the river bottom, and causing a shift in relative importance of planktonic algae over benthic algae in larger rivers. So nutrients generate problems with benthic algae in shallow streams and smaller rivers and planktonic algae in large rivers.

Nutrient effects on algae also vary depending upon the type of substratum in the river. Benthic algae can accumulate to much greater abundances when substrata are large cobble or bedrock that move relatively little in streams, because filamentous green macroalgae are more likely to grow in abundance on these substrata. Microalgae are the most common algae on smaller substrata and plants can grow in sediments.

Rain and resulting runoff to rivers and high flows can reset river ecosystems by scouring benthic algae from the bottom, washing planktonic algae to downstream lakes or the coastal zone, and replenishing nutrient supplies that may have been depleted during prior algae accumulation periods in the river. Following a high storm flow, benthic algae regrow and planktonic algae slowly accumulate downstream (Figure 4.2). Benthic invertebrates that graze algae can constrain algal accumulation if growth rates are low, but algae es-

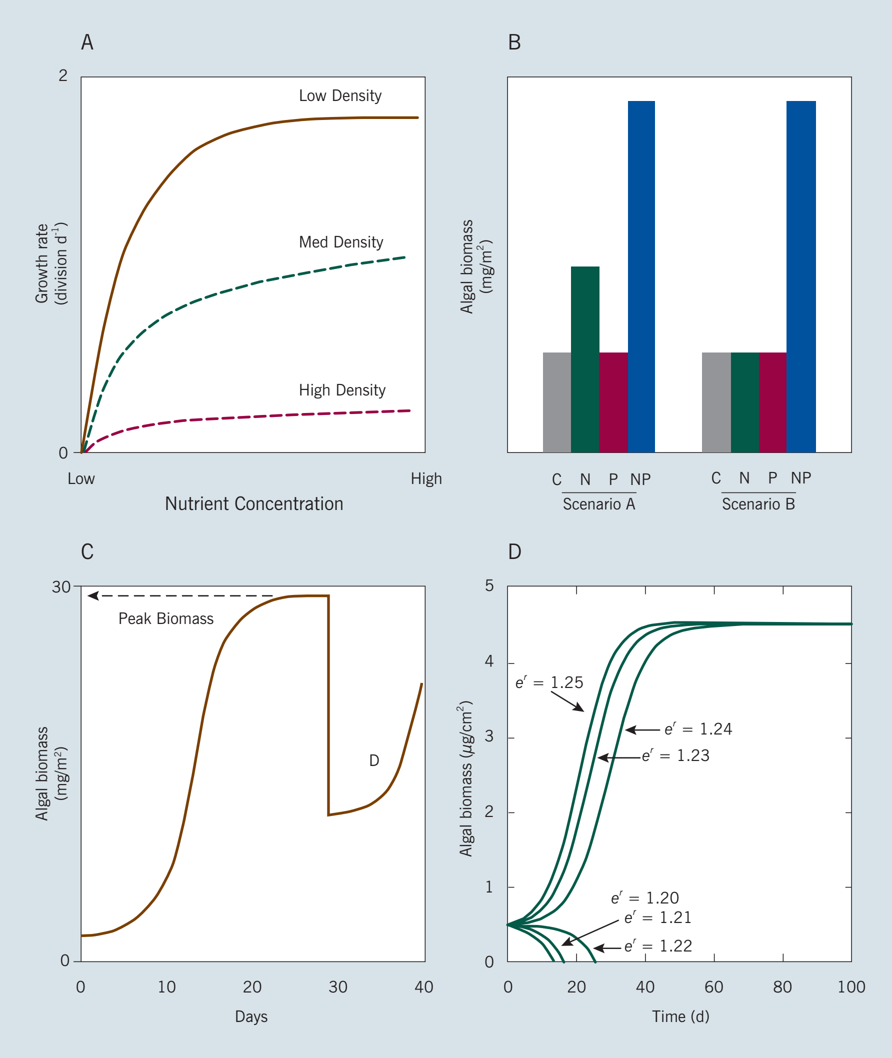


Figure 4.2:
Basic relationships between algal growth rates and nutrient concentrations. A) The asymptotic relationship between algal growth and nutrient concentrations, which decreases with algal density on substrata. B) Scenario A shows primary limitation of algal growth by nitrogen and secondary limitation by phosphorus. Scenario B shows colimitation by nitrogen and phosphorus. C) Benthic algal biomass starts out low after a storm event and grows to reach peak biomass in a 2-4 week period, after which it can slough from the substratum and then regrow. D) Results of simulation model showing sensitivity of algal accrual during assemblage development to slight changes in algal growth rate ($e^r = 1.20$-1.25) when herbivory is held constant

Source: Adapted from Stevenson (1997).

cape constraint when nutrients are high enough to produce growth rates that exceed grazing rates by invertebrates. The interaction of disturbance, algal recolonization, and potential constraint on algal accumulation by nutrient concentrations generates a threshold response in algal accumulation at the nutrient concentration that algae can outgrow grazing rates (Figure 4.2). As colonization time increases after a storm disturbance, the difference increases between algal accumulation in habitats with nutrients above and below the nutrient concentration threshold.

Effects of nutrient pollution on rivers vary with seasonal changes in light and temperature. Most problems with benthic algae in rivers are associated with filamentous macroalgae, such as the green alga *Cladophora* growing on rocks or the cyanobacterium *Lyngbya* growing in springs. The green alga *Cladophora* blooms when water temperatures are between 16 and 24°C (Figure 4.3). During cold seasons, diatoms are most abundant; and except for nuisance growths of some invasive species (such as *Didymosphaenia geminata*), diatoms are seldom a nuisance in streams. Planktonic algal blooms in rivers usually occur when low stable flows occur and nutrients are sufficiently high for algae to grow fast and accumulate. Most planktonic algal blooms are associated with warmer periods of the year, when rainfall is less frequent. Warm temperatures and nutrients stimulate algal growth, and warm temperatures favor the cyanobacteria. Many types of algae can cause taste and odor problems, as well as clog filters in water treatment plants, but the cyanobacteria can produce toxins that threaten human health.

Both nitrogen and phosphorus availability can limit algal growth in streams and rivers (Franceour et al. 2001). According to Liebig's Law of the Minimum, only one resource can limit growth and reproduction of a species at a time. With nitrogen and phosphorus being the most common limiting nutrient resources in rivers, three scenarios are possible for nutrient limitation (Figure 4.2B). In scenario A, algal growth is primarily limited by either low nitrogen or phosphorus concentration, and the other nutrient causes secondary limitation. In scenario B, increases in either nitrogen or phosphorus concentrations alone would not increase algal growth rates; concentrations of both nutrients must be increased to increase algal growth. In scenario C (not illustrated), both nitrogen and phosphorus concentrations are so high that increases in their availability would not stimulate further growth, so neither nitrogen or phosphorus availability limits algal growth. If nutrient concentrations are sufficiently low, either nitrogen or phosphorus would be limiting depending upon ratios of nutrient concentrations in the habitat. In most regions, phosphorus tends to be the most limiting nutrient. However, in regions with volcanic rock, nitrogen can be the primary limiting nutrient. In addition, terrestrial vegetation during the growing season can sequester sufficiently large quantities of nitrogen such that nitrogen may become limiting in streams.

Nutrient concentrations that limit algal growth vary greatly among species. Evidence from experimental streams and surveys of algal biomass in streams indicate a rule of thumb that peak algal biomasses are possible when total phosphorus is greater than 30 µg/L and total nitrogen is greater than 300 µg/L. In general, diatoms and most cyanobacteria have lower nutrient requirements

Figure 4.3:
A) A relatively natural occurrence of diatoms, the golden brown color on the stream bottom on either side of the storm-scoured central path in the middle of the stream and B) A nuisance growth of the green filamentous alga, Cladophora, *filling the stream*

than nuisance species of filamentous green algae. As algae accumulate in rivers, their densities can become sufficiently high that they deplete nutrient supplies. Thus nutrient concentrations in rivers that are higher than the 30 and 300 µg/L phosphorus and nitrogen concentrations can continue to cause greater algal biomasses because algae have sufficient nutrient supply to grow longer.

The relationship between biodiversity and nutrient pollution is more complex than single species growth-nutrient relationships. Nutrients negatively affect individual species indirectly by shifts in competitive hierarchies, grazer selection, and potential stimulation of bacteria, fungi, and viruses that cause disease in algae. Elevated nutrient concentrations make the habitat available for species requiring higher nutrients. Thus, the relationship between nutrients and algal biodiversity is a hump-shaped curve with a peak at intermediate nutrient concentrations. Low nutrient concentrations constrain which species can survive in the habitat and in high nutrient concentrations, habitats may be so altered physically and chemically by algal growth that some species of algae are not able to survive.

One of the critical questions in evaluating nutrient effects on algal biodiversity is whether species adapted to low nutrient concentrations are lost when nutrients increase from low to intermediate levels. In other words, as numbers of all algal taxa increase with increasing nutrients to intermediate concentrations because high nutrient taxa can invade, do we lose some highly sensitive taxa characteristic of natural, low nutrient conditions – our sensitive native species? Evidence suggests extirpation of diatom species in some streams as nutrient concentrations increase from low to intermediate levels. In large scale surveys of algae, we do not observe some taxa in intermediate and high nutrient habitats, even though these habitats were historically low nutrient habitats in which these taxa were characteristically abundant.

4.3. Nutrient effects on invertebrate and fish biodiversity

Invertebrate and some fish communities are strongly food limited in streams. Thus, nutrient driven increases in algal production have been observed to stimulate invertebrate and fish abundances. Fish and invertebrate biomass has been observed to increase two- to more than ten-fold in nutrient enriched rivers, and at large spatial scales, their biomass in rivers has been linked to phosphorus concentrations (Peterson et al. 1993). However, increased biomass does not mean increased biodiversity. In fact, negative effects of nutrients on invertebrate and fish biodiversity have been observed, especially in headwaters and wadeable streams. Nutrient enrichment leads to a decrease in pollution sensitive fish species, insectivores, and top carnivores, while omnivores and tolerant species increase. Similarly, carnivorous invertebrates and other pollution sensitive taxa decrease with nutrient enrichment as omnivorous invertebrates and tolerant species increase. State-wide surveys of fish and invertebrate biodiversity in the United States indicate that many attributes of biodiversity are negatively affected by nutrient concentrations. Independent results in West Virginia, Ohio, and

Box 4.2

Algal excess and oxygen: An apparent contradiction

Low dissolved oxygen in streams is caused by nutrients when they stimulate growth of autotrophs. This is often a perplexing relationship to understand, because we think most about how algae or aquatic plants add oxygen to streams. This is true, but algae and plants, like all other organisms, also respire to get energy that fuels metabolic reactions in cells. Those metabolic reactions make the proteins, lipids, and carbohydrates needed for cell function. So during respiration, oxygen is used and carbon dioxide is produced as a waste. The waste products of cell respiration, carbon dioxide and water, are used with light by algae and plants in photosynthesis, to produce sugars and oxygen. This cycling of carbon, hydrogen, and oxygen back and forth in the forms of carbon dioxide and water versus sugars and oxygen is one of the great balances in nature that occurs within a river and within our entire biosphere. The oxygen produced by autotrophs during the day can increase the oxygen concentration in streams. During both day and night they respire and use dissolved oxygen. Therefore, oxygen concentration in streams increases during the day if there is more photosynthesis than respiration, but it decreases at night because photosynthesis does not occur in the dark, just respiration. After a storm disturbance, algae and plants start regrowing, and as they accumulate day-night fluctuations in dissolved oxygen increase. When we add nutrients to rivers, autotrophs grow faster between storm events and thus fluctuations in dissolved oxygen

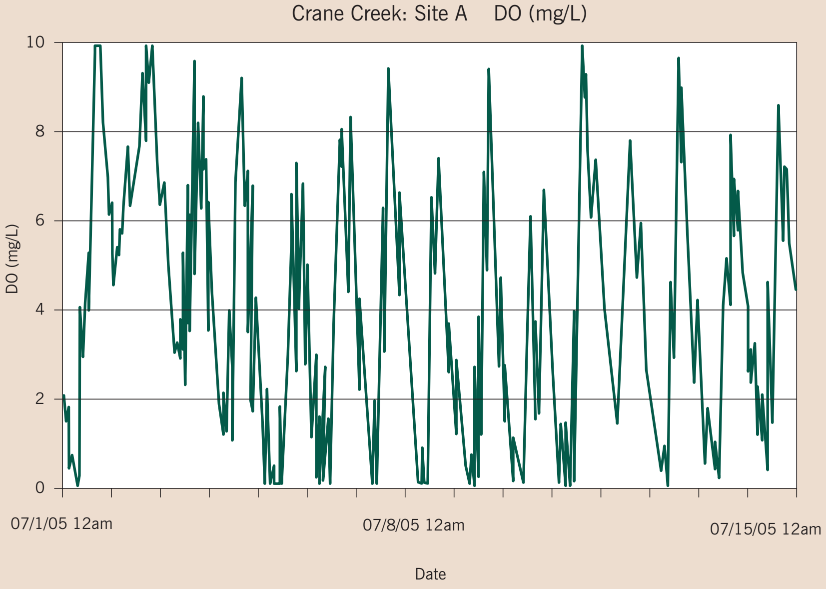


Figure 4.4: *Fluctuations in dissolved oxygen (DO, measured in milligrams/liter) during 24 hour cycles of light and dark periods in Crane Creek, a tributary of Lake Erie in the USA (figure courtesy of Michael J. Wiley, The University of Michigan). A storm disrupted algae on 7/1/2005. Afterwards algae and other biota in the stream regrew and produced greater and greater diurnal fluctuations in dissolved oxygen. Note how dissolved oxygen decreased to zero for longer periods of time on 7/7 and 7/12 in the early morning hours after previous light periods in which daytime oxygen concentrations stayed relatively low, perhaps caused by cloudy days*

Box 4.2 *(cont.)*: Algal excess and oxygen: An apparent contradiction

have greater amplitude and extend over longer periods of time. When fluctuations are really great, all oxygen in the stream can be used at night. Occurrence of these low oxygen events is difficult to predict, because they happen under relatively unusual weather patterns. But, when low oxygen conditions do occur, they can kill many organisms in the stream. This is one cause of fish kills in rivers. High pH, like low dissolved oxygen concentration, also stresses aquatic organisms and results from excess algal accumulation in a habitat. When algae photosynthesize, they consume carbon dioxide, which increases pH because of the role of carbon dioxide in a chemical equilibrium with carbonic acid and carbonates.

Wisconsin indicate that nutrients should be limited to less than 60 μg TP/L to protect the biodiversity of fish and invertebrates in their streams (e.g. Miltner and Rankin 1998).

Dissolved oxygen stress is the most commonly cited cause of loss in fish and invertebrate biodiversity with nutrient pollution, but physical habitat alterations by high algal accumulation and elevated pH are also issues. Excess growths of algae and associated bacteria can reduce oxygen concentrations and increase pH in streams. Dissolved oxygen is a limiting resource for fish and aquatic invertebrates. Government agencies around the world establish dissolved oxygen criteria between 4 and 6 mg/L and pH criteria of 9-10 to protect fish and invertebrate biodiversity. Lower dissolved oxygen concentrations than these criteria can be lethal to many species of fish and invertebrates (Davis 1975). Fish and invertebrate behaviour and reproduction are even more sensitive to lower dissolved oxygen than their death.

Response of fish and invertebrates to reduced dissolved oxygen varies greatly among species. The oxygen affinity of blood varies greatly among species. Many species of invertebrates don't have hemoglobin in their blood, so they have very limited affinity for oxygen circulation through their bodies and are more sensitive to low oxygen. Invertebrates have a great diversity of respiratory adaptations, ranging from gills, cutaneous respiration, and anal siphons. Anal siphons (tubes) allow mosquitoes to obtain oxygen from the air, which is why they bob with their bottoms toward the surface of the water. Top carnivores are probably highly sensitive to reduced dissolved oxygen because their bodies tend to be bigger and they have to be active to get their food. Variability in sensitivity among fish and invertebrate species to physical habitat alterations and pH has also been noted, but they have not been studied as thoroughly as oxygen sensitivity.

4.4. Challenges with measuring biodiversity responses to nutrients

Nutrient pollution exacerbates the challenging problem of estimating algal and invertebrate biodiversity in rivers. When hundreds of species occur in a habitat, tens of thousands of organisms must be observed to estimate the number of species in a habitat. Nutrient pollution increases the growth rates of species that require high nutrient concentrations. These high nutrient species often have very high maximum growth rates, resulting in very uneven abundances of species, with the rapidly growing high nutrient species having highest abundances. Uneven abundances of species create challenges for measuring biodiversity in rivers because more species will be relatively rare and not observed using routine methods for sampling and sample analysis.

Management of biodiversity requires a clear definition of goals and how and why what we learn is related to those goals. One rationale for protecting biodiversity (case 1), which is consistent with endangered species protection, is to protect the regional loss of species, or in case of highly valued game fish (e.g. salmon), loss of viable populations of evolutionarily and genetically distinct breeding populations. Protecting biodiversity, defined in this way, protects a final ecosystem service in which we have moral and aesthetic reasons for protecting species. Another reason for protecting biodiversity (case 2) is to protect the function of ecosystem services in the face of environmental change (Cardinale and Palmer 2002). In this case, we only need enough taxa to protect ecosystem function and related provisioning services. And finally, we have the concept of biological integrity, as defined by Karr and Dudley (1981), “the capability of supporting and maintaining a balanced, integrated, adaptive, community of organisms having species composition, diversity, and functional organization comparable to that of natural habitats of the region.” In the latter case (case 3), we manage nutrient pollution for minimally disturbed conditions and the species that characteristically occur in minimally disturbed conditions. Each of these definitions of biodiversity carry scientific challenges for measurement and quantitatively relating to nutrient pollution. In case 1 we need to measure all species in a habitat (true diversity), the species that are critical for supporting ecosystem function in case 2 (functional diversity), and a representative subset of all species that provide assurance that ecological conditions are minimally disturbed in case 3.

Exploring these scientific issues for protecting endangered species in rivers allows producing simplified models for exposing concepts in managing biodiversity. Let’s assume that our goal is to protect algal species from regional extirpation. Our definition of extirpation of a microalgal and bacterial species from habitats is poorly understood. Let's say we are interested in whether an algal species is extirpated from a stream. What is extirpation? Gone? Zero? As a wise microbial ecologist once said, "It only takes one" (Francis Drouet, Philadelphia Academy of Natural Sciences 1975). Because algae and microbes reproduce asexually and any single cell can then transform into a specialized cell for sexual reproduction, the successful reproduction and growth of just one cell is sufficient to restore the population of a microbial species in a stream. Given that cell densities of benthic algae and bacteria are commonly one billion cells per square meter of stream bottom, the number of cells in a stream is very large. Our routine method for ecological characterization of algae (and invertebrates) is examination of 300 cells in a sample from a stream. More thorough examinations sometimes call for 10,000 individuals in a sample, but this method is not used often. We never examine all the organisms from a habitat (except maybe trees, but then we do not sample all the seeds). The fact is, that we could be losing many more species than we observe missing because we did not know they were there to begin with. The problem with thinking about conservation of the biodiversity of microbes is that we have a very poor assessment of the true diversity of species in a habitat.

Although our understanding of the nutrient effects on rivers is not perfect, river science is sufficient to set nutrient management targets

In case 2 we are trying to estimate functional diversity, the identity and number of taxa that could grow and replace the function of lost taxa if environmental conditions changed. Functional diversity is also difficult to assess, but at least more practical than the true diversity of case 1. Modeling helps us understand requirements for assessing functional diversity. If we assume that we are trying to identify the species that could accumulate over a specific time period to replace ecosystem function of the dominant taxa, we need four pieces of information for the model: the length of time that species should have to replace the function of dominant taxa; the potential growth rates of the replacement taxa; abundance of dominant taxa (e.g. cells/cm^2); and the abundance of all cells (e.g. cells/cm^2) in the habitat of interest. Then, using the simple growth equation

$$N_t = N_0 e^{rt}$$

(where N_t and N_0 are the number of cells per unit area at time t in the future and time 0, the beginning; r is the growth rate (per day); and t is a number of days in the future)

we can estimate the number of cells that we would have to identify in a sample from the habitat to estimate functional diversity. We will assume: growth rates of algal cells in rivers are commonly 0.25 divisions d^{-1}; abundances of benthic algae are between 1-10 million cells per cm^2 of substratum; and we will allow one month

Practical management solutions can be applied to reduce and treat nutrient pollution to protect instream and downstream biodiversity and uses of water bodies

for rare species to recover and replace abundances of dominant species. Given these assumptions, one cell could accumulate to be about 2,000 cells in a month. It would take about 1,000 cells to accumulate to 2 million cells in 30 days and replace the function of an extirpated dominant species. If we had between 1 and 10 million cells in the habitat per cm^2, then we would have to examine between 1,000 and 10,000 cells to detect any species with 1,000 cells/cm^2 on day 0, which according to our model are species that could replace function of dominant taxa over a 30 day recovery period. If however, we allowed 60 days for recovery, which is a typical period of relatively consistent ecological conditions (a season) for algae in a river, then one cell could accumulate to be over 3 million cells with the same 0.25 division per day. To identify all algal taxa that could accumulate over a 60 day period and replace the function of past dominant taxa, given conditions as described, we would have to examine 3,000,000 cells. Thus, it is practical to estimate functional diversity of algae in rivers, but it will require more extended analyses of species composition of algae than we currently employ.

We have similar problems for characterizing biodiversity of aquatic invertebrates, plus an additional problem. First, the diversity of invertebrates in a habitat is very high; so observing most of the species in a habitat would require a large effort. In addition, we seldom evaluate species level occurrences of aquatic invertebrates in surveys, which is needed to inform assessments of endangered species. Many invertebrates are immature insect stages in rivers and many of those cannot be identified to species level. Most monitoring of aquatic invertebrates involves identifications of genus and higher levels of taxonomy. For algae and aquatic invertebrates, new molecular techniques offer the potential for high taxonomic resolution and high detection sensitivity. Fish and mussels are the two groups of organisms in aquatic habitats for which we can, with a level of accuracy appropriate for endangered species management, determine the presence and absence of species in a stream. Often the diversity of fish and mussel species is 30 or less in a habitat.

A practical solution for protection of biodiversity in rivers from effects of nutrients, given the challenges with measurement of true or functional diversity, is to manage rivers for ecological integrity, which is characterized by the physical, chemical, and biological condition of rivers that have very low levels of human alteration. This approach is based on a major tenet of conservation biology, that is, that preserving physical and chemical integrity of ecosystems will provide conditions for protecting biodiversity in that ecosystem. The methods for assessing physical, chemical, and biological conditions of rivers have been established and practiced in many parts of the world for ecological assessments that satisfy government regulations. These methods are becoming sufficiently accurate that the minimally disturbed condition for individual river segments can be predicted. They are also highly sensitive, such that modest changes in human disturbance can be detected. Thus, we can assess whether the biological integrity of Karr and Dudley (1981) is being met in a river segment and detect deviations from these conditions. If we assume that true and functional diversity are also protected, we have a reasonable and practical method for determining whether biodiversity of a site is being protected. Of course, it is possible that historic disturbances have caused extirpated species, but many lines of evidence suggest that rivers have great capacity for recovery if species are not regionally extirpated. If we protect the minimally disturbed habitats in which we observe many of the sensitive species that disappear with nutrient pollution and other stresses on river ecosystems, we are likely to protect the sensitive species that we have not observed.

4.5. Nutrient effects on ecosystem goods and services

Biodiversity is one of many goods and services provided by rivers and streams. Ecosystem goods and services are benefits to humans resulting from materials provided by or processes performed by ecosystems (MEA 2005). Obviously, rivers provide direct value to humans as a source of drinking water, which was historically relatively uncontaminated by human activities. Today, of course, most waters are contaminated by waste from humans that live upstream, so are unsafe for consumption without treatment or at least boiling. Even though great progress has been made toward goals of increasing availability of safe drinking water, over 600 million people are expected to lack that access in 2015 (UNEP 2012). In a very real way, transport of human waste away from their sources is an important service of rivers. Rivers, as well as associated wetlands and in-line lakes, are important for breakdown and transformation of those wastes into less toxic forms as well as their entrainment. Although waste transformation and transport are not ecosystem services for which economic markets exist, these services have value indirectly through other goods and services that result, such as cleaner downstream drinking water and sustainable fisheries.

Ecosystem goods and services have been grouped into four categories: provisioning, cultural, regulating, and supporting services. Water for drinking, irrigation, and industry, fish and shellfish, and hydropower are examples of provisioning services that have direct effects on human well-being and for which markets are commonly established. Cultural services are a bit more difficult to market, but they do have direct benefits for people. The aesthetic and recreational values of water for swimming, water sports, and fishing are examples of cultural services that have great economic importance. The support of biodiversity is also a cultural service from the perspective that for moral and spiritual reasons, people feel that protecting species is the right thing to do. Protecting species in ecosystems has also been related to protecting the sustainable functioning of ecosystems and the services they provide.

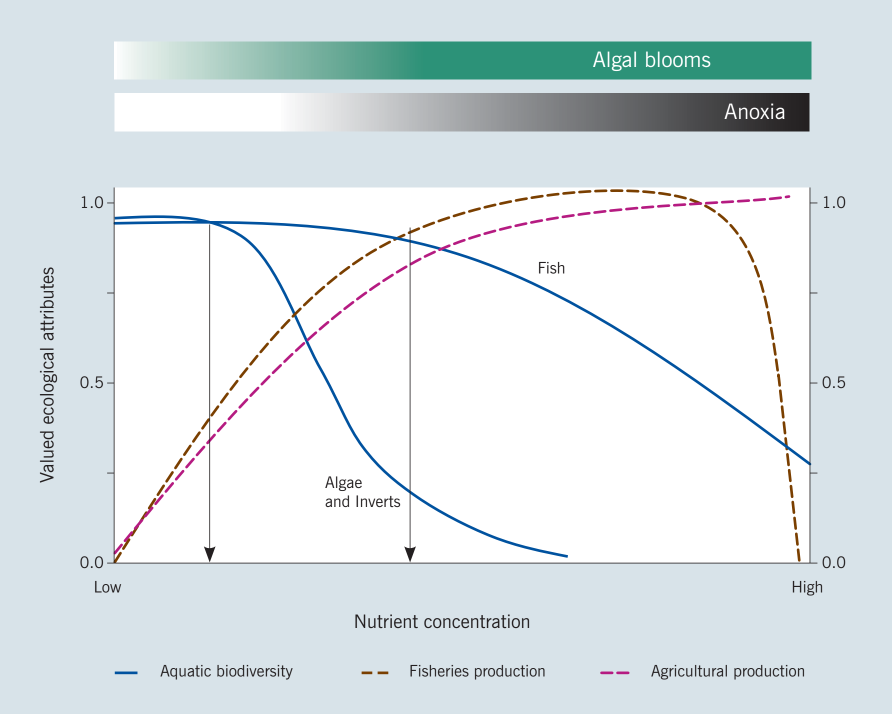
Provisioning and cultural services are referred to as final services, because they have direct benefits to humans. Two other categories of services, regulating and supporting services, are referred to as intermediate services because they do not directly benefit humans, but rather influence other services. Waste transport, biogeochemical transformation of wastes, organic matter processing, and nutrient cycling and retention are examples of regulating services. Regulating services transform ecological materials to mitigate leakage and disposal of wastes. Primary production, wildlife habitat, and resulting biodiversity can be considered supporting services, because they provide the resources for either regulating, provisioning or cultural services.

Effects of nutrient pollution on ecosystems services vary greatly among rivers in different geological, climatic, and economic settings. In addition effects of nutrient pollution present tradeoffs for managing rivers for different ecosystem services. Nutrient pollution negatively affects drinking water quality and most cultural services, likely including protection of sensitive taxa adapted to low nutrient concentrations (Figure 4.5). Most regulating services are positively affected by nutrient pollution, because increases in algal growth or nutrient concentrations would increase primary production, organic matter processing, and nutrient cycling. In addition, many provisioning services, for example fisheries, are positively affected by low and intermediate levels of nutrient pollution, but negatively affected by high levels.

4.6. Treatment and policy solutions for nutrient pollution management

Aquatic resource managers are faced with great challenges in nutrient pollution management because of tradeoffs in optimizing uses of ecological resources across regions. Tradeoffs are the fundamental challenge of managers (Ayensu et al. 1999). Tradeoffs occur at the scale of the habitat itself, with some ecosystem services of rivers being optimized at low levels of nutrient pollution and others at intermediate levels of nutrient pollution (Figure 4.5). Tradeoffs are compounded when resource uses of lands in a catchment are considered in the management plans that would optimize the uses of both terrestrial and aquatic ecological resources in a region.

Figure 4.5: *Tradeoffs among uses of rivers indicated by hypothetical relationships between a resource stressor (e.g. nutrient concentrations) and a suite of ecosystem services of catchments: drinking water quality; algal, invertebrate, and fish biodiversity; fisheries production; and agricultural production. The vertical lines indicate nutrient criteria that could be used to protect different uses in different waters*



Source: Modified from Stevenson and Sabater (2011).

Nutrient pollution is generated by many different alterations of a watershed by human activities. Relatively small amounts of nutrient pollution result from activities as simple as creating roads in a landscape or clearing vegetation from lands. This pollution results from several processes. First, clearing trees from land removes vegetation that sequesters nutrients. Removal of vegetation allows nutrients to leak from the catchment. Often, waste vegetation from logging operations releases nutrients as they decompose. Clearing trees from land and building roads can increase runoff of water and eroding sediments into streams. Increasing runoff and rates of groundwater percolation can also cause hydrologic instability in stream channels, which leads to stream bank failure and additional erosion. Sediments washing into streams carry large quantities of phosphorus relative to nitrogen. Groundwater carrying nutrients leaking from catchment to stream channels carries more nitrogen compared to phosphorus.

Application of fertilizers to agricultural lands and lawns in urban environments are major sources of nutrient pollution to rivers. Fertilizer runoff from croplands is a major source of nutrient contamination, and far exceeds runoff from pastures. We see evidence for this in much greater correlations in relationships between either nutrients or algal biodiversity in streams and the croplands versus pasture land in catchments. In fact, our greatest threat to future nutrient pollution is the added demands on agriculture (Seitzinger et al. 2010). Streams in more affluent neighborhoods have higher nutrient concentrations in them than streams in poorer neighborhoods because of ability of households to purchase fertilizer.

Wastes from humans and livestock are also major sources of nutrients. Wastes from humans and livestock are discharged to streams from either municipal or agricultural wastewater treatment plants, if these facilities exist, or directly through sewers, storm drains, or channels without treatment. Often manure or treatment plant sludge wastes are applied to both pastures and croplands for fertilizers, and in some cases as means to dispose of wastes rather than just fertilization. Wastes from humans and animals also enter rivers via runoff and groundwater when wastes come from isolated households with septic tanks or straight pipes into waterways. Some industrial processes also generate nutrient wastes as byproducts of processing large quantities of organic material. Pulp and paper mills and food processing operations are two examples. Organic wastes that accompany nutrients in human, animal, and some industrial wastes are particularly problematic because they also contribute to low oxygen in rivers, potentially synergistically with nutrients.

Many options exist for reducing and treating nutrient wastes, with some providing options for sustainable biofuels. Vegetated riparian buffer strips provide substantial reduction in phosphorus runoff from croplands, with benefits observed in improved algal biodiversity (chapter 9). Agricultural fertilizer waste could be reduced by educating farmers about determining fertilizer needs and the small benefits of over fertilization, testing nutrients in soils, taxing fertilizers, and developing better risk-distribution so farmers do not over fertilize to ensure they get a good crop. Waste-water treatment plants are being developed with advanced nutrient removal technologies. Problems remain however, in costs of implementing these technologies relative to perceived benefits. In fact, most costs are probably overestimated and most benefits are underestimated. Costs may be overestimated if some expenses can be recovered by using wastes to produce beneficial products, such as biofuels. Organic wastes can be used to produce methane and ethanol in anaerobic digestors. Nutrient by-products from anaerobic digestors and treatment facilities can be used to grow algae, which can also be used in biofuels. Nutrient wastes become a valuable commodity when they are linked to energy production, which could lead to a long-term sustainable solution to nutrient pollution.

Benefits of ecosystems goods and services are generally not appreciated by the public. But that is often because they are not informed about protecting the services and the values of services to them. The value of protecting biodiversity for many people in the world is high. This can be quantified as a direct benefit for the moral and aesthetic value of biodiversity to the public. The value of protecting biodiversity could also be estimated for increasing efficiency and sustainability of final ecosystem services, if we could quantify those relationships better and when we relate improved efficiency and sustainability of final ecosystem services to their values.

So what could the value of ecosystem goods and services of rivers be, and how are they impacted by nutrient pollution? These numbers are difficult to quantify for a variety of reasons, but approximations have been made. Economic implications of nutrient pollution for human health have not been estimated, but a recent assessment of damages to recreation, property values, and drinking water conservatively estimated damages between 2.2 and 4.6 billion US dollars per year in the United States alone (Dodds et al. 2009). Economic losses to boating and angling (US\$0.37 to US\$1.16 Byr^{-1}) and lake property values (US\$0.3 to US\$2.8 Byr^{-1}) were estimated to be particularly severe, followed by costs associated with contaminated drinking water (US\$0.81 Byr^{-1}), and mitigation of biodiversity impacts (US\$0.04 Byr^{-1}) (Dodds et al. 2009). These estimates are criticized by resource economists because they double count values of final and intermediate services; i.e. if the direct value of an intermediate ecosystem service is through the value of the final ecosystem service it regulates or supports, then summing values of intermediate and final services would be double counting. In addition, the methods of valuation are questioned because they assume that values of ecosystem services do not differ across landscapes. However, these numbers are sufficiently high to illustrate the great value of rivers and damages caused by nutrient pollution. Ecosystem service valuation will actually be very important factors in management strategies as weights in social preferences for acceptable risk for losing one ecosystem service versus another.

4.7. Management targets for nutrient pollution

Given we know relationships between nutrient concentrations, biodiversity, and other ecosystem services, and we can have technologies that can reduce and treat nutrient wastes, how low do we need to reduce nutrient pollution and where? What should nutrient management targets be? How and why would these nutrient management targets vary among rivers? How can we achieve these management targets? Significant advances in river science and ecology as well as nutrient treatment and environmental policy allow us to answer these questions better today than 10 years ago – and implement those answers in environmental policy.

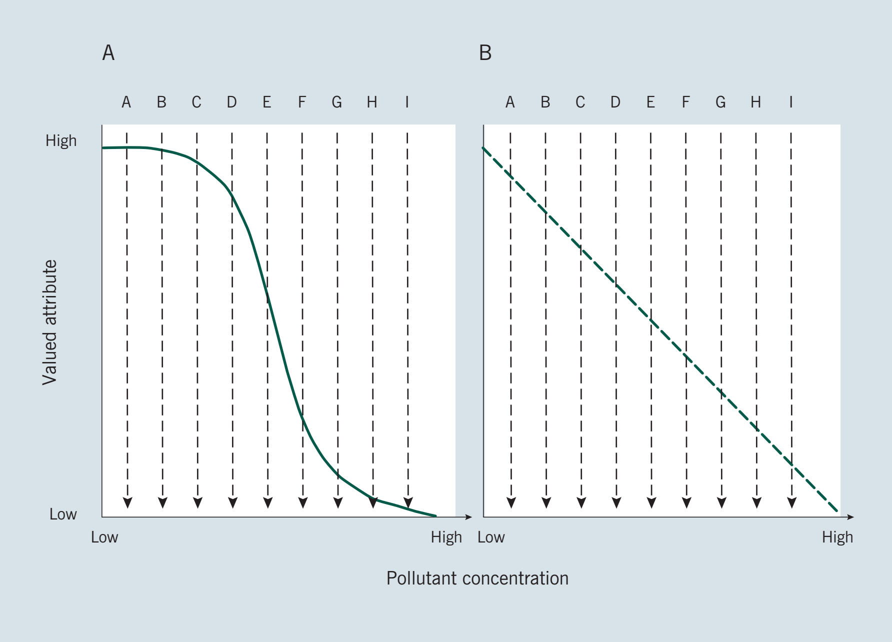
We can think of nutrient management targets as nutrient concentrations that provide an acceptable risk for sustaining an ecosystem service. In the US, these concentrations are referred to as nutrient criteria, which are part of water quality standards and related to protecting the specific uses of a waterbody. The designation of water body uses and related water quality criteria are codified in the rules of the Clean Water Act of the United States. Many other countries have similar laws and rules in which goals for pollution reduction are related to water resource uses, ranging from the European Union's Water Framework Directive to China's Water Pollution Prevention and Control Law. Historical application of the term "use" in its regulatory context is very similar to ecosystems services. Examples of regulatory uses of waters are drinking water, navigation, recreation, irrigation water, and aquatic life support (which is basically aquatic biodiversity). Thus, nutrient management targets are related to the uses of waterbodies.

Nutrient management targets are established in three different ways. One is to determine the lowest nutrient concentrations in a region where climatic and geological conditions are relatively similar and then apply those concentrations as targets for all waterbodies. This method is appropriate if large proportions of waterbodies are polluted in a region, if the pollution produces unacceptable changes in ecosystem condition, and if restoration of nutrient pollution to the lowest concentration in a region would provide benefits. Another method is to use characterizations of nutrient conditions at sites known to be meeting uses or meeting definitions of minimally disturbed (often called *reference*). Often the 75th percentile of nutrient concentrations at these sites provides appropriate upper bounds for a long-term average condition that will protect uses in similar waterbodies, but this approach does not specifically link nutrient concentrations to a problem. The last method is to explicitly and quantitatively relate nutrient concentrations to changes in measures of uses, determine desired level of uses, and use a model to determine the nutrient concentrations that provide the desired level of uses. The latter method is referred to as an effects-based approach (Figure 4.5). The effects-based approach is valuable because it explicitly relates use and contamination and it provides a means of evaluating tradeoffs among uses.

Thresholds in use-nutrient relationships are particularly valuable for establishing pollution criteria because they help develop stakeholder consensus (Muradian 2001). If a threshold relationship is observed in a valued attribute of an ecosystem, then the public tend to agree on a level of pollution that is acceptable for protecting a use. With threshold relationships the level of the valued attribute that is considered satisfactory is no longer a point of contention because the likelihood of protecting the valued attribute is either high or very low at different pollution levels, and presumable very low is unacceptable. Also the level of risk of losing the attribute is less a point of contention, because the range in pollution levels at which the valued attribute goes from high to low is very narrow.

The graph in Figure 4.6 provide an opportunity to explore the value of thresholds in relationships between a valued attribute and pollution concentration for environmental policy. Take this simple quiz. Assume that Figure 4.6A shows the relationship between something we really care about (life savings, happiness of our children, biodiversity) and a "pollutant" (volatility in stock markets, global strife and inequality, nutrients). What is the maximum level of pollutant to which you would be willing to expose your valued positions or feelings? Would you choose stressor level A, B, C, D, E, F, G, H, I? Most people pick B or C. Remember this is losing something that you really care about. Would you be willing to lose 5-10% of it? What if there was uncertainty about the level of stressor that occurs from year to year? That would likely cause you to pick even lower levels of pollution. In real ecosystems, there is uncertainty from year to year. If we

Figure 4.6:
A) Threshold responses in a valued ecological attribute, or bad attribute, help stakeholders develop consensus on appropriate pollution levels for protecting ecosystem. B) A linear response in a valued attribute along a stressor gradient



only want to allow modest reductions in a valued attribute every 5-10 years, then B becomes the answer more than C. Curves with some assimilative capacity like Figure 4.6A allow for some stress in the system before collapsing. Figure 4.6B shows a relationship with a linear response, in which agreement is much more difficult because there is no one level of the pollutant that has a substantially lower effect than a slightly higher value of the pollutant. The challenge with a linear responses is that either no pollution is allowed, or the selected level of pollution allowance becomes difficult to justify to stakeholders with a diversity of opinions.

If tradeoffs in uses exist along gradients, then all uses of waters cannot be supported at optimal levels using the same nutrient management target. For example, if nutrient pollution reduces biodiversity but increases fisheries production (Figure 4.5), then is optimizing at low or high levels of pollution desirable? If we manage for intermediate levels of pollution, then we do not get optimal levels or potentially even satisfactory levels of either use. In fact, we may have lost considerable biodiversity at levels of nutrient pollution that provide fisheries and even moderate levels of agriculture or urban development in catchments. Different nutrient management targets must be used for different waterbodies to support all uses at satisfactory levels in one location or another. Low targets for nutrient management would protect biodiversity, water quality and recreational uses, but may not provide high productivity for fisheries or allow extensive agriculture in watersheds (Figure 4.5). Intermediate levels of nutrients have moderate risk to drinking water and recreational uses, but enable extensive agriculture in a watershed. If sufficiently low numbers of rivers are managed at intermediate levels of nutrient pollution, perhaps downstream uses could be protected as well. Allowing for different uses of different water bodies enables managing sets of rivers to protect all uses and achieving higher aggregate regional use benefits than by managing all waterbodies at the same level of pollution.

In addition to tradeoffs, another reason to manage waterbodies for different and site-specific levels of nutrient pollution is the impracticality of protecting all waterbodies for the low levels of pollution that would be necessary to protect sensitive species. First, the levels of nutrients that affect biodiversity in rivers are relatively low compared to concentrations observed in many regions of the world having even modest human alteration of catchments. Second, extensive contamination of soils and groundwater with nutrients makes restoration of some catchments difficult. Thus a reasonable strategy is to select one subset of all rivers to protect for uses related to biodiversity and drinking water and another subset of rivers could be established to protect uses for fisheries productivity and allow human alterations of landscapes at relatively extensive levels.

A minimum goal for all waters should be limiting nutrient pollution so that rivers continue to provide high levels of some ecosystem services and protect downstream conditions.

To achieve these goals for regional optimization, new questions emerge. Two questions are fundamental. What are the different uses for rivers in a region? How many and which rivers should be protected for the different uses? While it is beyond the scope of this chapter to address all factors associated with this question, we will show that the question can be addressed with sufficient accuracy that answers can be used for development of nutrient management policy.

First, a major issue for determining the number of rivers to conserve for different uses in a region is the values that regional people have for different ecosystem services. Valuation of ecosystem services varies internationally for a variety of factors, but particularly economic conditions. For example, greater value is placed on recreational and aesthetic conditions of rivers in affluent than poor regions. In many parts of the world, managing nutrients to protect biodiversity is not a priority for local or national governments. In fact, adding nutrients increases productivity for aquaculture which has great value for providing food in poor countries (Figure 4.7). Of course, the result is often more harmful algal blooms and low oxygen concentration in downstream rivers and lakes, which harm drinking water supply, human health, and fisheries. Integrated resource management can be used to evaluate the costs and benefits of different management strategies as well as identify who is responsible for damage and who should pay for restoration or lost resources, if that is necessary.

The question of how many rivers to manage for different uses also depends on the diversity of uses of rivers and surrounding ecosystems, tradeoffs among those uses, and acceptable risks for not supporting uses. For example, how many rivers must be managed to reduce nutrients to control hypoxia in coastal waters? Watershed models can provide a reasonable answer to that question for developing management strategies. How many rivers should be managed for recreational fisheries? Again, economic valuation of recreational fisheries can be estimated, as well as distance of rivers from potential users, which together could be used to develop an optimization model for river management. How many streams should be protected for species and which streams should be protected? Addressing these questions calls for understanding spatial meta-population dynamics and in particular, dispersal, colonization, and local extinction rates of organisms (Lowe 2002). Fewer habitats would need protection if dispersal rates, connectivity of habitats, and sub-population persistence are high. Because of the punctuated nature of low dissolved oxygen events in streams, maintaining high quality dispersal

Figure 4.7: *The stark realities of tradeoffs among uses of our waters are evident when traveling around the world. Nutrient management of waters in some parts of the world means adding nutrients to the water, rather than reducing nutrient pollution. Here are pictures of a farm in the Mekong River Delta of Vietnam. Manure from the pig is used to produce methane for cooking in a homemade anaerobic digestor. Then waste from the digestor is put into a canal to increase algal and bacterial production to grow fish as fast as possible. The fish adapt to the low oxygen concentrations in these waters by gulping air from the surface of the water*

pathways for organisms may not be critical for those organisms if they can use contaminated pathways during low stress periods. At larger spatial scales, sets of streams should be selected from different climatic and geological settings as well as streams and rivers of different size because these streams would support the broadest diversity of organisms.

Scientists, policy makers, and other stakeholders are poised for major changes in environmental policy for nutrient management of rivers. Important instream and downstream problems are caused by nutrients in rivers, ranging from loss of biodiversity to impairment of drinking water, recreational, and fisheries uses. Whereas urban wastewater and agriculture have been major sources of nutrients in the last 50 years, increases in non-point source nutrients from agriculture needed to feed a growing world population likely present the greatest future threat to nutrient management. Solutions exist to minimize over fertilization and for nutrient harvesting in algal biofuels. Sound science will be critical and is available for developing nutrient management policy, as well as conceptual advances of linking science and policy. The great importance of these environmental problems to human well being calls for additional investment in science to refine solutions to these problems, but the lack of perfect knowledge is not justification for inaction. On the contrary, uncertainty in knowledge calls for greater caution and need for conservation. The time for action is now. We need local and national governments, as well as governments around the world, to cooperate on environmental policy. In particular, an internationally consistent nutrient management policy could protect biodiversity as well as other ecosystem goods and services in both instream and downstream waters. A policy, using site-specific goals for management, effects-based pollution criteria, and a long-term vision for achieving these goals could serve as a model for managing other cross-boundary environmental problems.

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