About Issues in Ecology

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Issues in Ecology

Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen

Photo by Brett Johnson

Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen

SUMMARY

Runoff from our farms and cities is a major source of phosphorus (P) and nitrogen (N) entering rivers, lakes, and coastal waters. Acid rain and airborne pollutants generated by human activities also supply N to surface waters. These nutrient sources are called “nonpoint” because they involve widely dispersed activities. Nonpoint inputs are difficult to measure and regulate because of their dispersed origins and because they vary with the seasons and the weather. Yet nonpoint inputs are the major source of water pollution in the United States today, and their impacts are profound. In aquatic ecosystems, over-enrichment with P and N causes a wide range of problems, including toxic algal blooms, loss of oxygen, fish kills, loss of seagrass beds and other aquatic vegetation, degradation of coral reefs, and loss of biodiversity — including species important to commercial and sport fisheries and shellfish industries. Thus, nutrient fouling seriously degrades our marine and freshwater resources and impairs their use for industry, agriculture, recreation, drinking water, and other purposes.

Based on our review of the scientific literature, we are certain that:

- Eutrophication caused by over-enrichment with P and N is a widespread problem in rivers, lakes, estuaries, and coastal oceans.
- Nonpoint pollution is a major source of P and N to surface waters of the United States. The major sources of nonpoint pollution are agriculture and urban activity, including industry and transportation.
- In the U.S. and many other nations, inputs of P and N to agriculture in the form of fertilizers exceed outputs of those nutrients in the form of crops.
- High densities of livestock have created situations in which manure production exceeds the needs of crops to which the manure is applied. The density of animals on the land is directly related to nutrient flows to aquatic ecosystems.
- Excess fertilization and manure production cause a P surplus, which accumulates in soil. Some of this surplus is transported in soil runoff to aquatic ecosystems.
- Excess fertilization and manure production create a N surplus on agricultural lands. Surplus N is mobile in many soils, and much leaches into surface waters or percolates into groundwater. Surplus N can also volatilize to the atmosphere and be redeposited far downwind as acid rain or dry pollutants that may eventually reach distant aquatic ecosystems.

If current practices continue, nonpoint pollution of surface waters is virtually certain to increase in the future. Such an outcome is not inevitable, however, because a number of technologies, land use practices, and conservation measures are available that can decrease the flow of nonpoint P and N into surface waters.

From our review of the available scientific information, we are confident that:

- Nonpoint pollution of surface waters with P and N could be decreased by reducing excess nutrient flows in agricultural systems, reducing farm and urban runoff, and reducing N emissions from fossil fuel burning.
- Eutrophication of aquatic ecosystems can be reversed by decreasing input rates of P and N. However, rates of recovery are highly variable, and recovery is often slow.

The panel finds that the roots of the problem of nonpoint pollution and eutrophication are well understood scientifically. There is a critical need for creative efforts to translate this understanding into effective policies and practices that will lead to protection and recovery of our aquatic resources.

Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen

by
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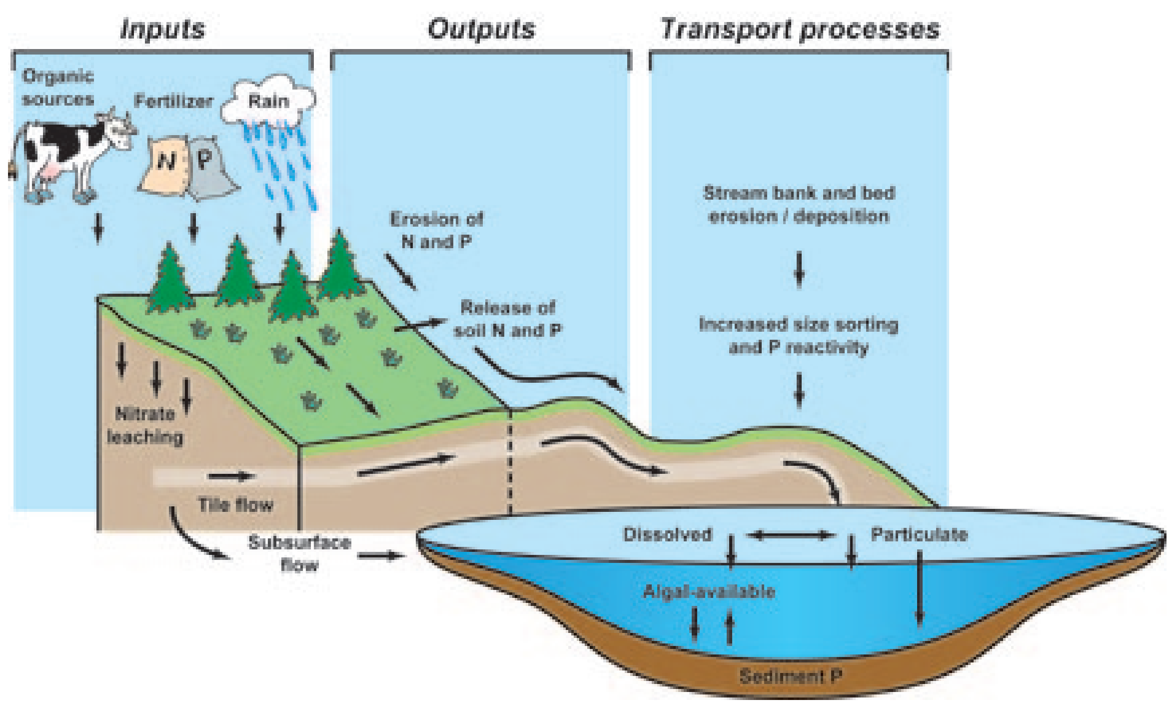
INTRODUCTION

From ancient times, people have chosen to live near water, settling in river valleys, beside lakes, or along coastlines. The attractions of water are as diverse as human needs and aspirations. Clean water is a crucial resource for drinking, irrigation, industry, transportation, recreation, fishing, hunting, support of biodiversity, and sheer esthetic enjoyment. For as long as humans have lived near waterways, they have also used them to wash away and dilute society's wastes and pollutants. But with growing populations and increased production and consumption, this long tradition of flushing wastes downstream has begun to overwhelm the cleansing capacities of the Earth's waters. Pollutant inputs have increased in recent decades, and the result has been degradation of water quality in many rivers, lakes and coastal oceans. This degradation shows up in the disruption of natural aquatic ecosystems, and the consequent loss of their component species as well as the amenities that these ecosystems once provided to society. Water shortages, for instance, are increasingly common and likely to become more severe in the future. Water shortages and poor water quality are linked, because contamination reduces the supply of water and increases the costs of treating water to make it safe for human use. Thus, preventing pollution is among the most cost-effective means of increasing water supplies.

The most common impairment of surface waters in the U.S. is eutrophication caused by excessive inputs of phosphorus (P) and nitrogen (N). Impaired waters are defined as those that are not suitable for designated uses such as drinking, irrigation, industry, recreation, or fishing. Eutrophication accounts for about half of the impaired lake area and 60% of the impaired river reaches in the U.S. and is also the most widespread pollution prob-



Artwork by W. Feeny

Figure 1 - Nutrients in manure and fertilizers are transported to lakes, rivers, and oceans. Excessive nutrient inputs result in degradation of water quality, causing the disruption of aquatic ecosystems.

Sources of Point and Nonpoint Pollution

POINT SOURCES	NONPOINT SOURCES
• Wastewater effluent, both municipal and industrial • Runoff and leachate from waste disposal sites • Runoff and infiltration from animal feed lots • Runoff from mines, oil fields, and unsewered industrial sites • Storm sewer outfalls from cities with a population of greater than 100,000 • Runoff from construction sites larger than two hectares • Overflows of combined storm and sanitary sewers	• Runoff from agriculture (including return flow from irrigated agriculture) • Runoff from pasture and range • Urban runoff from unsewered areas and sewered areas with a population of less than 100,000 • Septic leachate and runoff from failed septic systems • Runoff from construction sites smaller than two hectares • Runoff from abandoned mines • Atmospheric deposition over a water surface • Activities on land that generate contaminants, such as logging, wetland conversion, construction and development of land or waterways

Figure 2 - Sources of point and nonpoint chemical inputs to lakes, rivers, and oceans recognized by statutes. Pollutant discharges from point sources tend to be continous and therefore relatively simple to identify and monitor. Nonpoint sources, however, arise from a suite of activities across large areas and are much more difficult to control.

lem of U.S. estuaries. Other important causes of surface water degradation are siltation caused by erosion from agricultural, logging, and construction activities (silt also carries nutrients, contributing to eutrophication); acidification from atmospheric sources and mine drainage; contamination by toxins; introduction of exotic species such as zebra mussels and sea lampreys; and hydrologic changes created by dams, channelization, draining of wetlands, and other waterworks.

Chemical inputs to rivers, lakes, and oceans originate either from point or nonpoint sources. Point sources include effluent pipes from municipal sewage treatment plants and factories. Pollutant discharges from such sources tend to be continuous, with little variability over time, and often they can be monitored by measuring discharge and chemical concentrations periodically at a single place. Consequently, point sources are relatively simple to monitor and regulate, and can often be controlled by treatment at the source. Nonpoint inputs can also be continuous, but are more often intermittent and linked to seasonal agricultural activity such as planting and plowing or irregular events such as heavy rains or major construction. Nonpoint inputs often arise from a varied suite of activities across extensive stretches of the landscape, and materials enter receiving waters as overland flow, underground seepage, or through the atmosphere. Consequently, nonpoint sources are difficult to measure and regulate. Control of nonpoint pollution centers on land management practices and regulation of the release of pollutants to the atmosphere. Such controls may affect the daily activities of millions of people.

In many cases over recent decades, point sources of water pollution have been reduced, owing to their relative ease of identification and control. However, point sources are still substantial in some parts of the world and may increase with future expansion of urban areas, aquaculture, and factory "farms," such as hog factories. This report focuses on nonpoint sources, not because point sources are unimportant, but because nonpoint inputs are often overlooked and pose a significant environmental challenge.

Nonpoint inputs are the major source of water pollution in the U.S. today. The National Water Quality Inventory stated in 1988 that "the more we look, the more we find." For example, 72% to 82% of eutrophic lakes would require control of nonpoint P inputs to meet water quality standards, even if point inputs were reduced to zero.

This report primarily addresses nonpoint pollution of water by P and N because:

- Eutrophication is currently the most widespread water quality problem in the U.S. and many other nations.
- Restoration of most eutrophic waters requires the reduction of nonpoint inputs of P and N.
- A sound scientific understanding of the causes of nonpoint nutrient pollution exists. In many cases, we have the technical knowledge needed to decrease nonpoint pollution to levels compatible with water quality standards.
- The most important barriers to control of nonpoint nutrient pollution appear to be social, political, and institutional. We hope that our summary of the scientific basis of the problem will inform and support debate about solutions.

WHY IS NONPOINT P AND N POLLUTION A CONCERN?

Eutrophication: Scope and Causes

Eutrophication means the fertilization of surface waters by nutrients that were previously scarce. Over geologic time, eutrophication through nutrient and sediment inflow is a natural aging process by which warm shallow lakes evolve to dry land. Today human activities are greatly accelerating the process. Freshwater eutrophication has been a growing problem for decades. Both P and N supplies contribute to it, although for many lakes excessive P inputs are the primary cause.

Eutrophication is also widespread and rapidly expanding in estuaries and coastal seas of the developed world. For most temperate estuaries and coastal ecosystems, N is the element most limiting to production of plant material such as algae (primary productivity), and so N inputs are the most problematic. Although N is the major factor in eutrophication of most estuaries and coastal seas, P is also an essential element that contributes to coastal eutrophication. It is, in fact, the dominant control on primary production in some coastal ecosystems.

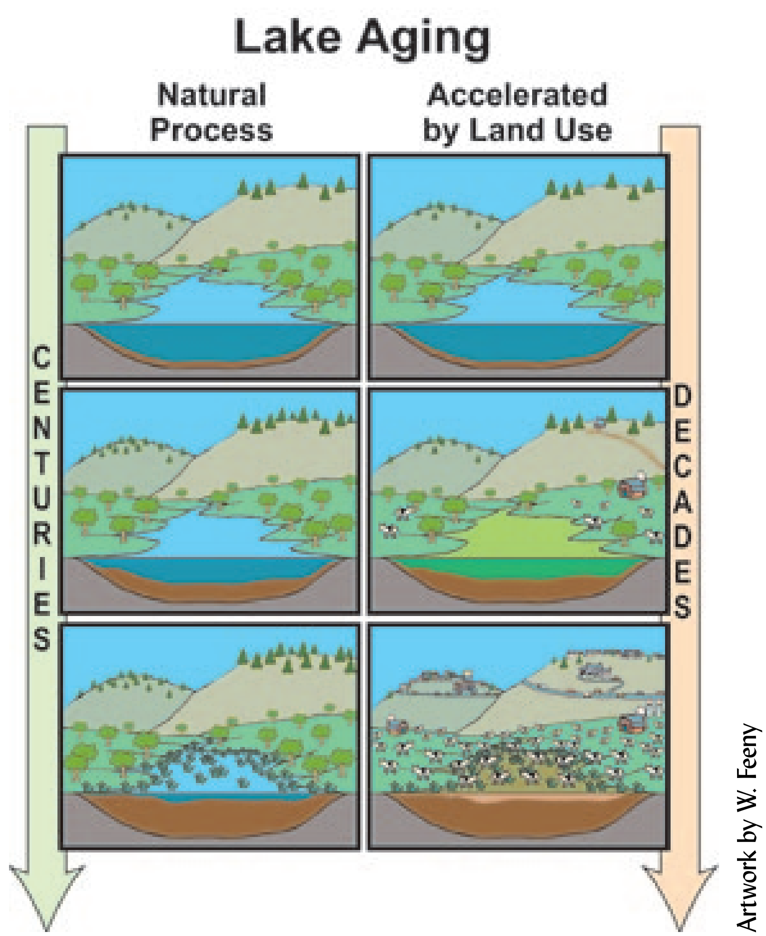


Figure 3 - Over extended periods of time, lakes tend to fill with sediment through natural processes (left). Currently, changes in land use and nutrient inputs are accelerating this process, filling lakes with sediments and algal blooms in just a few years (right).

Consequences

Eutrophication has many negative effects on aquatic ecosystems. Perhaps the most visible consequence is the proliferation of algae, which can turn water a turbid green and coat shallower surfaces with "pond scum." This increased growth of algae and also aquatic weeds can degrade water quality and interfere with use of the water for fisheries, recreation, industry, agriculture, and drinking. As overabundant nuisance plants die, bacterial decomposers proliferate; as they work to break down this plant matter, the bacteria consume more dissolved oxygen from the water. The result can be oxygen shortages that cause fish kills. Eutrophication can lead to loss of habitats such as aquatic plant beds in fresh and marine waters and coral reefs along tropical coasts. Thus, eutrophication plays a role in the loss of aquatic biodiversity.

Explosive growths of nuisance algae are among the most pernicious effects of eutrophication. These algae produce structures or chemicals that are harmful to other organisms, including livestock or humans. In marine ecosystems, algal blooms known as red or brown tides cause widespread problems by releasing toxins and by spurring oxygen depletion as they die and decompose. The incidence of harmful algal blooms in coastal oceans has increased in recent years. This increase is linked to coastal eutrophication and other factors, such as changes in marine food webs that may increase decomposition and nutrient recycling or reduce populations of algae-grazing fish. Algal blooms have severe negative impacts on aquaculture and shellfisheries. They cause shellfish poisoning in humans, and have caused significant mortality in marine mammals. A toxic dinoflagellate known as Pfiesteria has been associated with mortality of finfish on the U.S. Atlantic coast. The highly toxic, volatile chemical produced by this dinoflagellate can also cause neurological damage to people who come in contact with it.

In freshwater, blooms of cyanobacteria (formerly called blue-green algae) are a prominent symptom of

Adverse Effects of Eutrophication

- Increased biomass of phytoplankton
- Shifts in phytoplankton to bloom-forming species which may be toxic or inedible
- Increases in blooms of gelatinous zooplankton (marine environments)
- Increased biomass of benthic and epiphytic algae
- Changes in macrophyte species composition and biomass
- Death of coral reefs and loss of coral reef communities
- Decreases in water transparency
- Taste, odor, and water treatment problems
- Oxygen depletion
- Increased incidence of fish kills
- Loss of desirable fish species
- Reductions in harvestable fish and shellfish
- Decreases in perceived esthetic value of the water body

Figure 4 - Eutrophication, caused by excessive inputs of phosphorus (P) and nitrogen (N), has many adverse effects on lakes, reservoirs, rivers, and coastal oceans (modified from Smith 1998).

eutrophication. These blooms contribute to a wide range of water-related problems including summer fish kills, foul odors, and unpalatable tastes in drinking water. Furthermore, when such water is processed in water treatment plants, the high load of organic detritus reacts with chlorine to form carcinogens known as trihalomethanes. Water-soluble compounds toxic to the nervous system and liver are released when cyanobacterial blooms die or are ingested. These can kill livestock and may pose a serious health hazard to humans.

Contribution of Nonpoint Pollution

Nonpoint sources are now the dominant inputs of P and N to most U.S. surface waters. Nonpoint inputs of P cause eutrophication across a large area of lakes and reservoirs in the U.S. Nonpoint sources are also the dominant contributors of P and N to most rivers in the U.S., although point sources still generate more than half of the P and N flowing into rivers from urbanized areas. In one study of 86 rivers, nonpoint N sources were responsible for more than 90% of N inputs to more than half these rivers. Nonpoint P sources contributed over 90% of the P in a third of these rivers.

For many estuaries and coastal seas, nonpoint sources are the dominant N inputs. Along the entire coastline of the North Atlantic Ocean, for instance, nonpoint sources of N are some 9-fold greater than inputs from wastewater treatment plants. In some coastal areas, however, wastewater treatment plants remain the primary source of N inputs. And although nonpoint inputs of P are often significant, point sources supply the highest inputs of P in many marine environments.

Remediation

Reversal of eutrophication requires the reduction of P and N inputs, but recovery can sometimes be accelerated by combining input controls with other management methods. In fact, active human intervention may be necessary in some cases because the eutrophic state is relatively stable in lakes. Some internal mechanisms that may hamper recovery from this degraded state include continuing release of P from accumulations in lake-bottom sediments, loss of submerged plants whose roots served to stabilize sediments, and complex changes in the food web such as decreases in grazing fish or zooplankton that helped to control growth of nuisance algae. Less is known about the stability of eutrophication in estuaries and coastal oceans, but the eutrophic state may be more easily disrupted and remedied there because in open, well-mixed coastal oceans nutrients may be diluted and flushed away rapidly. However, in relatively confined, shallow marine waters such as the Baltic Sea, nutrients may be trapped and eutrophication may be as persistent as it is in lakes.

Direct Health Effects

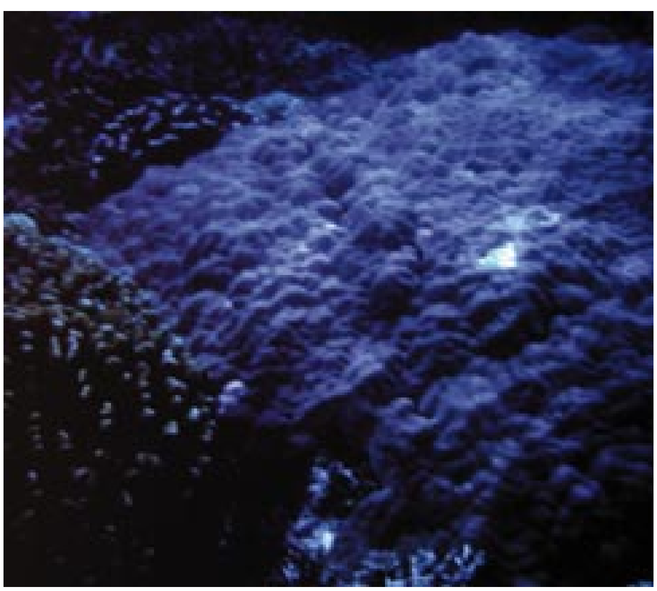
Phosphorus in water is not considered directly toxic to humans and animals, and because of this, no

Photo by Chris Luecke

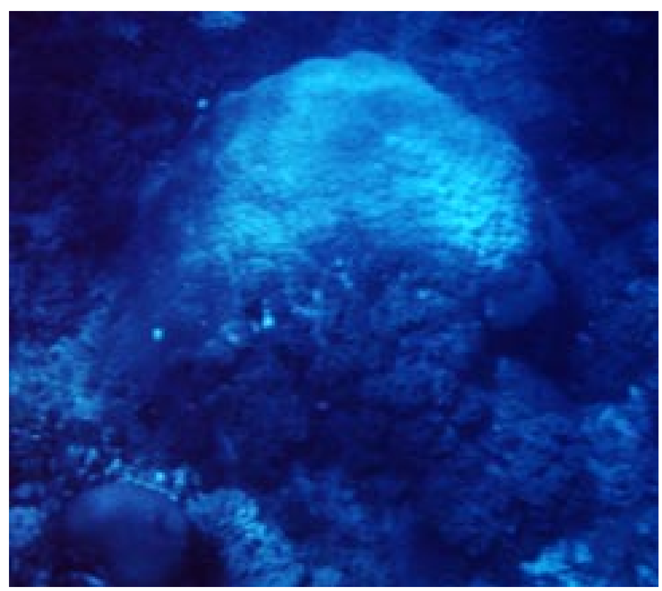
Figure 5 - Nitrogen and phosphorus pollution causes increased incidents of fish kills. Fish die because of toxic algal blooms or the removal of oxygen from the water as algal blooms decay.

drinking water standards have been established for P. Any toxicity caused by P pollution in fresh waters is indirect, through stimulation of toxic algal blooms or resulting oxygen depletion.

In contrast, nitrate pollution poses a direct health threat to humans and other mammals. Nitrate in water is toxic at high concentrations and has been linked to toxic effects on livestock and also to "blue baby disease" (methemoglobinemia) in infants. The Environmental Protection Agency has established a Maximum Contaminant Level for nitrate-N in drinking water of 10 milligrams per liter to protect babies under 3 to 6 months of age. This age group is most sensitive because bacteria that live in an infant's digestive tract can reduce nitrate to nitrite, which oxidizes hemoglobin and interferes with the oxygen-carrying ability of blood. In cattle, nitrate reduced to nitrite can also be toxic and causes a similar type of anemia as well as abortions. Levels of 40-100 milligrams of nitrate-N per liter in livestock drinking water are considered risky unless the animals' feed is low in nitrates and fortified with vitamin A.



Photos by R.W. Buddemeier, Kansas Geological Survey



Figures 6 and 7 - Eutrophication can lead to the loss of habitats such as coral reefs, therefore contributing to the loss of aquatic biodiversity. Note the healthy growth and coverage of hard corals in the figure on the left, versus the less diverse soft corals resulting from human disturbance, including increased turbidity, in the area of the reef shown on the right.

WHAT ARE THE SOURCES OF NONPOINT POLLUTION?

Nonpoint P and N pollution is caused primarily by agricultural and urban activities. In the U.S., agriculture is the predominant source of nonpoint pollution. Wind or rain-borne deposits from a variety of sources, including agriculture and fossil fuel burning, can add significant amounts of N to surface waters.

Agriculture

On the world's croplands, human additions and removals of nutrients have overwhelmed natural nutrient cycles. Globally, more nutrients are added as fertilizers than are removed as produce. Fertilizers are moved from areas of manufacture to areas of crop production. The nutrients in the fertilizer are only partly incorporated into crops, which are then harvested and transported to other areas for consumption by people or livestock. Thus on balance, there is a net transport of P and N from sites of fertilizer manufacture to sites of fertilizer deposition and manure production. This flux creates a nutrient surplus on croplands, and this surplus is the underlying cause of nonpoint pollution from agriculture.

Figure 8 - Intensive animal production, where large numbers of animals are concentrated in small feedlots, creates enormous amounts of waste, causing excess nutrients to build up in the soil, run off, or infiltrate water supplies.

Fertilizer

Phosphorus is accumulating in the world's agricultural soils. Between 1950 and 1995, about 600 million metric tons of fertilizer P were applied to Earth's surface, primarily on croplands. During the same time period, roughly 250 million metric tons of P were removed from croplands in the form of harvested crops. Some of this produce was fed to livestock and a portion of the manure from these animals was reapplied to croplands, returning some of the harvested P (about 50 million metric tons) to the soil. Thus the net addition of P to cropland soils over this period was about 400 million metric tons. This excess P may either remain in soils or be exported to surface waters by erosion or leaching. The majority of applied P remains on croplands, with only 3 to 20% leaving by export to surface waters. It is likely, therefore, that about 350 million metric tons of P has accumulated in the world's croplands. The standing stock of P in the upper 10 centimeters of soil in the world's croplands is roughly 1,300 million metric tons. That means that a net addition of 350 million metric tons between 1950 and 1995 would have increased the P content of agricultural soils by about 25%. In the U.S. and Europe, only about 30% of the P input in fertilizers ends up being incorporated into crop plants, resulting in an average accumulation rate of 22 kilograms of surplus P per hectare each year. Across whole watersheds, the amount of P applied to agricultural soils in excess of what plants can use is closely linked to eutrophication of surface waters.

Global industrial production of N fertilizers has increased steeply from nearly zero in the 1940s to roughly 80 million metric tons per year. In the U.S. and Europe, only 18% of the N input in fertilizer leaves farms in produce, meaning that on average, 174 kilograms per hectare of surplus N is left behind on croplands each year. This surplus may accumulate in soils, erode or leach to surface and ground waters, or enter the atmosphere. N is added to the atmosphere through volatilization of ammonia and microbial generation of nitrous oxide gas from soils. Nitrous oxide contributes to global warming and can also catalyze the destruction of stratospheric ozone. Much of the N volatilized to the atmosphere in these forms is rained out or redeposited in dry forms on land or water and eventually enters rivers, lakes, and other aquatic ecosystems.

Manure

Intensive animal production generally involves feeding large numbers of animals in small areas. For example, 4% of the cattle feedlots in the U. S. produce 84% of the cattle. Such large concentrations of animals

Figure 9 - Runoff from urban activities, such as lawn fertilizers and pet wastes, is a significant source of nonpoint pollution that we can all help to control.

create enormous amounts of waste. The disposal problems are comparable to those for raw human sewage, and yet the regulatory standards for disposing of animal wastes are generally far less stringent than the standards cities and towns must meet for treating human sewage.

Nutrients in manure can be recycled by applying the manure to cropland. However, the amount of manure generated by concentrated livestock operations often far exceeds the capacity of nearby croplands to use and retain the nutrients. At typical stocking rates for feedlots, for instance, an area of cropland roughly 1,000 times greater than the feedlot area itself is required to distribute manure nutrients at levels equal to what the crops on that land can use. This much accessible cropland may not be available, so excess quantities of manure are applied to smaller land areas. The excess nutrients then build up in soil, run off, or infiltrate to water supplies. Or, in the case of N, they may enter the atmosphere.

Transport to Aquatic Ecosystems

Increased fluxes of P and N to surface waters have been measured after application of fertilizer or manure to farm land. Fertilizer P and N losses in runoff are generally less than 5% of the amount applied. Losses from manure can be slightly higher (up to 20% if rain falls immediately after application). However, these percentages underestimate total N flux to aquatic ecosystems because they do not include infiltration and leaching which ultimately carry N to ground and surface waters. N export from agricultural ecosystems to water, as a percentage of fertilizer inputs, ranges from 10% to 40% for loam and clay soils to 25% to 80% for sandy soils. In general, the rates of nutrient loss to water from fertilizer and manure are influenced by the rate, season, chemical form, and method of nutrient application; amount and timing of rainfall after application; and the plant cover. The greater proportional losses of P and N from manure than from industrially produced fertilizers may result from higher P and N concentrations in manure and less flexibility in the timing of applications, since manure must be worked into soils before or after the growing season rather than at the time growing crops require P and N.

The amount of P lost to surface waters increases with the P content of the soil. The loss can come in the form of dissolved P, but even more P is transported as particles. In the long term, this particulate P can be converted to phosphate and made available to aquatic organisms.

N transport to the oceans has increased in recent decades and the increase can be correlated to a number of human activities that increase N inputs into watersheds. Similarly, the amount of P carried in rivers to the oceans is positively correlated with human population density in watersheds. Globally, the movement of P to coastal oceans has increased from an estimated pristine flux rate of 8 million metric tons per year to the current rate of 22 million metric tons per year. About 30% of this increase is attributed to P enrichment of agricultural soils, and the remainder to increasing rates of erosion.

Urban Runoff

A significant amount of P and N enters lakes, rivers, and coastal waters from urban nonpoint sources such as construction sites, runoff of lawn fertilizers and pet wastes, septic systems and developed areas that lack sewers. Urban runoff is the third most important cause of lake deterioration in the U. S., affecting about 28% of the lake area that does not meet water quality standards.

Urban point sources of water pollution, such as sewage and industrial discharges, are also significant, but unlike nonpoint sources, they are often managed intensively.

Construction sites are a critical concern as sources of nonpoint pollution. Although construction sites may occupy a relatively small percentage of the land area, their erosion rates can be extremely high and the total nonpoint pollution yield quite large. Erosion rates from watersheds under development approach 50,000 metric tons per square kilometer a year, compared to 1,000 to 4,000 metric tons per square kilometer for agricultural lands and less than 100 metric tons for lands with undisturbed plant cover. Eroded material from construction sites contributes to siltation of water bodies as well as eutrophication.

Atmospheric Deposition of N

N deposited to surface waters from the atmosphere arises from several sources, including trace gases released from farm soils and the burning of fossil fuels. Combustion of fuels such as coal and oil releases significant quantities of nitrogen-based trace gases into the atmosphere, both by oxidizing organic N stored in the fuels themselves and by directly "fixing" molecular N from the air during high temperature, high pressure combustion. (Fixing N involves pulling it from the air and bonding it to hydrogen or oxygen to form compounds that plants and other organisms can use.) Currently, some 20 million metric tons of fixed N per year are released globally from fossil fuel combustion by automobiles, factories, and power plants. However, this represents only one-fourth of the amount of N used in inorganic N fertilizer and perhaps one-seventh of the total amount of N fixed globally through human activity, including the manufacture of inorganic fertilizers and the planting of N-fixing crops such as soybeans and other legumes. Nonetheless, N from fossil fuel combustion may contribute substantially to the nonpoint-source pollution of surface waters.

A comparative study of N fluxes from 33 rivers in the northeastern U.S. found that the amounts of both nitrate and total N in the rivers were correlated with the atmospheric deposition of oxidized N — which comes largely from fossil fuel combustion — onto the watersheds of these rivers. For a small subset of these rivers, historical data showed an increase in nitrate concentrations from the early 1900's to the present. The increase in nitrate concentrations correlates with estimates for increased fossil fuel emissions of N during the same period.

We still have much to learn about the transport of atmospherically-derived N from land to water. Clearly the atmosphere can be a significant source of N to lakes and rivers and make potentially large contributions to coastal eutrophication. And we know that volatilization of nitrogen-based gases from agricultural land supplies a significant fraction of this N.

WHAT CAN BE DONE ABOUT IT?

Unless current practices are changed, nonpoint pollution of surface waters will increase in the future. Some factors that drive this expectation are the substantial and growing buildup of P and N in agricultural soils; an increasing human population; people's preference for meat-rich diets, which mandates increasing livestock production; growth of urban areas with associated development and erosion; and increased fixation of N by human activities such as fertilizer production and fossil fuel burn-

Photo by S.C. Delaney/EPA

Figure 10 - The high erosion rate of construction sites is a major source of runoff from developing areas. Eroded materials contribute to siltation and eutrophication of lakes, rivers, and coastal oceans.

ing. (Ironically, the increasing use of more efficient engines and turbines for burning fossil fuels has had the inadvertent effect of increasing the fixation of N.)

However, this pessimistic forecast could prove to be incorrect, because there are a number of ways that nonpoint pollution can be reduced. Here we offer a brief catalog.

Landscape Management

Forests and other vegetation along riverbanks and shorelines can significantly reduce the flow of nonpoint nutrients into surface waters. This vegetation also makes important contributions to fish and wildlife habitat and regional biodiversity. Interest in the use of riparian vegetation for controlling nonpoint pollution has grown rapidly in recent years, and the number of scientific studies and articles on the subject has burgeoned.

Wetlands, lakes, and rivers are sites of denitrification — a bacterial process that breaks down organic N and releases it to the atmosphere, decreasing the flow of N to downstream ecosystems. Restoration of wetlands and floodplains is likely to increase denitrification at a landscape scale and to some extent reduce N pollution of lakes and rivers. Thus, wetland restoration may be the most cost-effective method of decreasing nonpoint N pollution.

Photo by S.C. Delaney/EPA

Figure 11 - There are a number of ways that nonpoint source pollution can be reduced. For example, restoration of wetlands and increasing riparian vegetation intercepts nonpoint pollution and also provides wildlife habitat.

Agricultural P and N Management

The ultimate causes of nonpoint pollution from agricultural lands are excessive fertilizer use and development of high-density livestock operations. There are direct solutions. Fertilizer applications can be reduced to match crop needs. Wastes from high-density livestock operations can be managed as a point source of pollution just like human wastes. Nutrients in manure can be used as fertilizer, or nutrients can be removed (as in human sewage treatment) before wastes are discharged to surface waters. Work to implement these solutions now focuses on establishing the threshold levels at which soil nutrients threaten water quality, identifying intensive sources of pollutants, and developing mechanisms for controlling both nutrient sources and transport.

Thresholds

Threshold levels of soil nutrients that create unacceptable threats to water quality must be established in order to provide a firm basis for regulations that protect aquatic resources. Defining thresholds has been controversial, in part because data are insufficient. Unfortunately, the data base relating soil nutrient concentrations to runoff is limited to a few types of soils and crops, making it difficult to extrapolate these data to all regions. Because costs of nutrient management are significant, the agricultural industries most likely to be affected by thresholds have vigorously challenged their scientific basis. A stronger scientific foundation can and should be developed for soil nutrient thresholds so that scientifically based standards can be promulgated and defended.

Source Area Delineation

Typically, more than 90% of the P export from watersheds originates from less than 10% of the land area during a few large storms. Thus, remedial measures will be most effective if they are targeted to source areas of P export. These are lands that combine high soil P concentrations with characteristics that enhance erosion and surface runoff.

Source Management

N and P runoff can be greatly reduced if fertilizers are applied at rates that match the N and P uptake by crops, and if fertilizers are applied when crops are growing rapidly. Also, dietary P inputs to livestock can be matched to the animals' requirements, which would decrease the amounts of P excreted in manure. Source management can significantly reduce concentrations of P in runoff entering streams and lakes. For example, aggressive treatment of dairy wastes in Florida reduced total P concentrations in surface water by 62% to 87%.

Transport Management

Transport of P and N from croplands to surface waters by erosion and runoff may be reduced by maintaining vegetated riparian zones or buffer strips, creating retention ponds, or adopting farming practices such as conservation tillage, terracing, contour tillage, and cover crops. Vegetated buffer strips in riparian zones, for example, reduce P transport to streams by 50% to 85%. However, such solutions must be combined with reductions in nutrient sources to soils or soil nutrients will continue to accumulate.

Control of Urban Runoff

Control of urban nonpoint pollution is a well-developed branch of civil engineering with an extensive and sophisticated literature. One key goal is optimization of sewer systems. Other approaches include creation of retention ponds, wetlands, and greenways as integrated components in stormwater management systems; litter control and street sweeping; reduction of impervious areas such as concrete and asphalt pavement that enhance runoff; and reduction of erosion, especially from construction sites.

Atmospheric Deposition

Atmospheric deposition of N can be reduced by more efficient use of fertilizers and improved handling of animal wastes. Thus, steps needed to reduce surface movement of agricultural N will also reduce atmospheric transport. Reductions in fossil fuel combustion, and improved interception of nitrogen trace gases generated during fossil fuel combustion, will also reduce airborne N deposition.

CONCLUSIONS

We already have a sound fundamental understanding of the processes that cause nonpoint pollution and eutrophication. The causes and consequences are clear at both regional and global scales. Our capacity for site-specific analyses of nonpoint sources and their impacts is well-developed and improving. While science alone cannot solve the problem, the panel believes the necessary science is available and could be readily mobilized in the search for solutions. The most critical need now is for the development of creative policy and regulatory mechanisms that mesh the science with social realities and chart a course for reducing nonpoint pollution and mitigating eutrophication of our waterways.

FOR FURTHER INFORMATION

This report summarizes the findings of our panel. Our full report, which is being published in the journal *Ecological Applications* (Volume 8, Number 3, August 1998) discusses and cites more than 70 references to the primary scientific literature on this subject. From that list we have chosen those below as illustrative of the scientific publications and summaries upon which our report is based.

Naiman, R. J., J. J. Magnuson, D. M. McKnight, and J. A. Stanford. 1995. The Freshwater Imperative. Island Press, Washington D. C.

National Research Council. 1992. Restoration of Aquatic Ecosystems: Science, Technology and Public Policy. National Academy Press, Washington D.C.

Novotny, V. and H. Olem. 1994. Water Quality: Prevention, Identification and Management of Diffuse Pollution. Van Nostrand Reinhold, NY.

Postel, S.L. and S.R. Carpenter. 1997. Freshwater ecosystem services. Pages 195-214 in G.C. Daily, editor, Nature's Services. Island Press, Washington D.C.

Vitousek, P. M., J. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and G. D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. Ecological Applications 7: 737-750.

About the Panel of Scientists

This report presents a consensus reached by a panel of six scientists chosen to include a broad array of expertise in this area. This report underwent peer review and was approved by the Board of Editors of *Issues in Ecology*. The affiliations of the members of the panel of scientists are:

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About the Science Writer

Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

About Issues in Ecology

Issues in Ecology is designed to report, in language understandable by non-scientists, the consensus of a panel of scientific experts on issues relevant to the environment. *Issues in Ecology* is supported by a Pew Scholars in Conservation Biology grant to David Tilman and by the Ecological Society of America. All reports undergo peer review and must be approved by the editorial board before publication.

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Previous Reports

Previous *Issues in Ecology* reports available from the Ecological Society of America include:

Vitousek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences, *Issues in Ecology* No. 1.

Daily, G.C., S. Alexander, P.R. Ehrlich, L. Goulder, J. Lubchenco, P.A. Matson, H.A. Mooney, S. Postel, S.H. Schneider, D. Tilman, and G.M. Woodwell. 1997. Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems, *Issues in Ecology* No. 2.

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